UNIVERSITÉ DE MONTRÉAL

DESIGN FOR DISASSEMBLY AND SUSTAINABILITY ASSESSMENT TO SUPPORT AIRCRAFT END-OF-LIFE TREATMENT

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DEDICATION

To my great parents, my little brother, and Alina; for your never ending support, encouragement, patience, and love!

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RÉSUMÉ

L’industrie aéronautique se développe vers une économie circulaire avec la réutilisation de ses matériaux et composants. Pourtant, chaque année, des centaines d’avions finissent à l’enfouissement sans un traitement approprié. Pour faire face à ce problème, cette recherche s’est principalement concentrée sur deux approches à savoir **l’amélioration de la conception des avions en fin de vie au niveau de la phase de développement** et **l’amélioration des méthodes de traitement** pour les avions retirés du marché lesquelles ont été conçus il y a des décennies.

L’amélioration des produits durant sa phase de développement apparait comme une solution prometteuse pour maximiser le taux de revalorisation du produit. En attendant, le désassemblage apparait comme une activité évidente autant à la fin de vie du produit que durant sa période de fonctionnement (par exemple la maintenance des avions). Dans cette thèse, une nouvelle approche est introduite en vue d’être implémentée durant la phase de conception d’un avion, afin d’améliorer le désassemblage futur des avions en fin de vie. Pour ce faire, les travaux de désassemblage seront abordés comme un problème de prise de décision multicritères. Cinq paramètres sont considérés sur la base des expériences accumulées durant les travaux de désassemblage d’un avion régional Bombardier : « l’accessibilité », « les surfaces de contact », « les outils requis », « les types de connections » et « la quantité et les variantes des différentes connections ». Une méthode d’évaluation par pointage utilisant les méthodes de « conception pour l’expérimentation » (en anglais « Design of Experiment », ou l’acronyme « DOE ») et TOPSIS est développée. Les résultats d’ANOVA ont montré un taux de fiabilité de 94.3 % confirmant la pertinence du modèle. Le modèle proposé peut être facilement utilisé par les décideurs et les concepteurs en vue de la réingénierie, pour améliorer le désassemblage et, plus généralement, la valorisation des futurs avions en fin de vie.

En vue d’améliorer les méthodes de traitement pour la fin de vie des avions, nous avons implémenté huit différentes stratégies de désassemblage/démantèlement sur la carcasse de l’avion mentionné ci-dessus. La durabilité et le développement durable deviennent de plus en plus le centre d’attention des industries. Agissant comme un fournisseur pour des industries plus influentes, les entreprises de démantèlement/recyclage devraient se concentrer sur des stratégies leur permettant une amélioration de leurs positions sur le marché. Un des facteurs clé serait de pratiquer la durabilité et le développement durable dans tous les procédés de démantèlement et de recyclage. En ce sens, les huit stratégies employées ont été évaluées et comparées en termes de durabilité. Dix-neuf indicateurs ont été définis afin d'évaluer les impacts environnementaux, sociaux et économiques de chaque stratégie. Un système d'inférence floue a été utilisée pour prendre en considération les incertitudes et les imprécisions des indicateurs. Ce système d'inférence floue conduit au développement d'une évaluation de la durabilité en utilisant une technique d'inférence floue (en anglais « fuzzy-inference technique » ou « SAFT » pour l'acronyme) pour évaluer la durabilité du produit/procédé à différent stage de son cycle de vie. Contrairement aux techniques traditionnelles de systèmes de logique floue, la plateforme proposée ne nécessite pas la génération de règles, simplifiant ainsi la procédure et sa mise en pratique.

ABSTRACT

Despite aerospace industries are moving toward circular economy and reutilization of materials and components, every year hundreds of aircrafts end up in landfills without an appropriate treatment. To address this problem, this thesis has been focused on two main approaches: **amelioration of aircraft design for end-of-life at the development phase** and **improvement of end-of-life treatment methods** for aircrafts that have been designed decades ago and are currently retired.

Amelioration of product design at the development phase stands as a very promising approach to increase the product recoverability rate. Meanwhile, disassembly appears as an inevitable activity for products not only at the end-of-life but also during the products life time and maintenance. In this thesis, a new approach is introduced to be implemented at the design phase for improving aircraft disassemblability at the end-of-life. For that, disassembly job was tackled as a multi-criteria decision-making problem. Five parameters were considered based on the experience accumulated during the disassembly work on a Bombardier Regional Jet aircraft: "Accessibility", "Mating face", "Tools required", "Connection type", and "Quantity and variety of connections". A novel disassembly scoring model using a hybrid design of experiment (DOE) and TOPSIS method was developed. The results from ANOVA showed a 94.30% of reliability, and testified the adequacy of the model. The proposed model can be easily used by decision-makers, and designers for reengineering purposes to improve the disassembly and in a broader scope recoverability of the future aircrafts at the end-of-life.

Towards the improvement of end-of-life treatment methods, in this work we have implemented eight different disassembly/dismantling strategies on the carcass of the above mentioned aircraft. Sustainability and sustainable development are more and more becoming the center of attention for different industries. Acting as a supplier for bigger industries, aircraft dismantler/recycler businesses should focus on strategies that allow to ameliorate their current position in the market. One of the key factors is to practice sustainability and sustainable development in all the dismantling and recycling processes. In this direction, the eight strategies employed were evaluated and compared in terms of sustainability. 19 indicators were defined to assess the environmental, social, and economic impacts of each strategy. The input data were provided from the experts who were engaged into the strategies implementation. A fuzzy inference system was applied to handle

the uncertainties and vagueness existent in the nature of the indicators. This fuzzy-inference system led to the development of a sustainability assessment using fuzzy-inference technique (SAFT) to evaluate sustainability of products/processes at different stages of product life-cycle. Unlike other fuzzy rule-based techniques, this proposed platform does not require generation of rules which simplifies the procedure and makes it more practical.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

1.1 Problem statement

It is a fact that in big industries (aerospace, naval, construction, etc.) the major profit is generated during the use phase. Hence, most efforts are put for manufacturing and use phases in products life-cycle, while less attention are being paid to disassembly and end-of-life. There are thousands of retired aircrafts parked in remote deserts or airports; and this figure is increasing every year. Storing an out of service aircraft is not a long-term viable solution due to the costs associated, the maintenance required, and the risk of losing the assets intrinsic value. Therefore, actions need to be taken right after the aircraft is confirmed as non-airworthiness; and prioritizing the maximum value that can be recovered. For that, different end-of-life treatments have to be implemented in a tight relation with the type of aircrafts that are currently getting to end-of-life and were designed decades ago without taking into account an appropriate design for end-of-life. Thus far, the end-of-life treatments applied on aircrafts have been focused on increasing the material homogeneity through some disassembly/dismantling strategies from which there is a poor information available published. Although, these pre-shredding strategies may improve the material homogeneity, it is highly important to evaluate the sustainability associated to them. To assess the environmental, economic, and social impact adds value to the products/processes and place the aircraft dismantlers/recyclers in a better position in terms of market competitiveness.

On the other hand, in order to facilitate the aircrafts recyclability, efforts should be strongly focused to include the design for end-of-life at the early stage of development phase. Several design methodologies have been proposed to be applied for end-of-life suitability such as: design for recycling, design for environment, design for disassembly, design for rebirth, etc. The efficiency of all these design methods is associated to a proper disassembly. However, disassembly job cannot be seen as a static process since the disassemblability of the components may vary through the process depending on the “disassembly state”. Therefore there is a need for a dynamic model that allows to assess the relationships among the components in terms of disassembly at the development phase.

To address these issues, in this thesis we have made the following hypothesis.

1.2 Hypothesis

- *A model based on parameters that have controllable characteristics at the design phase can allow to evaluate the disassemblability of the components at the development phase*.
- *Finding and analyzing the appropriate indicators allows to assess the sustainability performance of different disassembly/dismantling strategies implemented on an aircraft*.
- *Applying a measure of "disorder" in the collected data allows to extract the expert knowledge individually and find a consensus among the different judgements.*

1.3 Research objective

The conventional management systems for aircraft end-of-life are not sufficient and responsive to deal with the increasing amount of retired aircrafts every year. Thus, the efforts should be focused on developing more innovative and intelligent strategies to compensate the existent deficiencies in the design and recover as much as possible in a sustainable way. The general goal of this thesis is to develop methods to evaluate disassembly at the design phase (for aircrafts of new generation) and the sustainability performance of end-of-life strategies (for aircrafts that were designed decades ago and are currently at the end-of-life) to support aircraft recycling based on current disassembly/dismantling technology.

For that, the specific objectives of this work are defined as follows:

- To develop a model to evaluate disassemblability of the components based on the experience accumulated during the disassembly job on a Bombardier Regional Jet aircraft.
- To evaluate the sustainability performance and describe different disassembly/dismantling strategies implemented on the case study aircraft.

- To develop an interactive tool to help designers evaluating their products/processes in terms of sustainability and sustainable development.

1.4 Thesis organization

Including this introduction, in following chapter, Chapter 2, a detailed revision on the current issues in the field of aircraft end-of-life is provided; Chapter 3 presents a model based on a decision-making approach in order to evaluate disassemblability of products at the design phase. To achieve this, "design of experiment" and "technique for order preference based on similarity to ideal solution" were combined to obtain a unique discriminant disassembly model. The methodology and results for this chapter have been published in:

- Sabaghi, M., Mascle, C., Baptiste, P., (2016). "Evaluation of products at design phase for an efficient disassembly at end-of-life". *Journal of Cleaner Production*, Volume 116, Pages: 177-186. (Impact Factor: 4.96)

- Sabaghi, M., Mascle, C., Baptiste, P., (2015). "Application of DOE-TOPSIS technique in decision-making problems", In *Marek B. Zaremba, Alexandre Dolgui (Editors), 15th Symposium on Information Control Problems in Manufacturing. International Federation of Automatic Control (IFAC), May 11-13, 2015 Ottawa, Canada. IFAC-PapersOnLine*, Volume 48, Issue 3, Pages: 773-777.

In Chapter 4 are presented the disassembly/dismantling strategies implemented on an end-of-life aircraft and they were evaluated in terms of sustainability by fuzzy analysis of the pertinent elements defined. To achieve this, pertinent indicators were established in a hierarchical structure and an appropriate technique was used to deal with the uncertainty and fuzziness derived from the expert's evaluation. The work presented in this chapter has been published in:

- Sabaghi, M., Cai, Y., Mascle, C., Baptiste, P., (2015). "Sustainability assessment of dismantling strategies for end-of-life aircraft recycling". *Resources, Conservation and Recycling*, Volume 102, Pages: 163-169. (Impact Factor: 3.28)

- Sabaghi, M., Cai, Y., Mascle, C., Baptiste, P., (2016). "Toward a sustainable disassembly/dismantling in aerospace industry". In *Holger Kohl, Günther Seliger (Editors),* *13th Global Conference on Sustainable Manufacturing. September 16-18, 2015 Ho Chi Minh City, Vietnam. (Procedia CIRP)*, Volume 40, Pages: 156-161.

Application of a fuzzy-inference system is proposed in Chapter 5 for extended sustainability evaluation of general products/processes. To achieve this, an entropy-based “fuzzy analytical hierarch process” was developed as a sustainability assessment fuzzy-inference technique (SAFT) such that there is no need for rules generation. The SAFT methodology has been published in:

- Sabaghi, M., Mascle, C., Baptiste, P., Rostamzadeh, R., (2016). “Sustainability assessment using fuzzy-inference technique (SAFT): A methodology toward green products”. *Expert Systems with Applications*, Volume 56, Pages: 69-79. (Impact Factor: 2.98)
- Sabaghi, M., Mascle, C., Baptiste, P. “Product sustainability evaluation: A tool to measure sustainability of products”. In *Somen Chowdhury, James Corrigan, Michel Dion (Organizers), International Conference on Environmental Sustainability in Air Vehicle Design and Operations of Helicopters and Airplanes, Sustainability 2015*, September 22-24, 2015 Montreal, Canada.

Chapter 6 discusses the results achieved in each chapter; and finally Chapter 7 presents the conclusion.

Since this thesis has been organized in the paper-based format, the corresponding bibliography and necessary appendices were added at the end of Chapters 3, 4, and 5.

CHAPTER 2 LITERATURE REVIEW

This chapter presents an overview on the state of the art related to aircraft end-of-life. The revision has been focused on the major issues in this field such as the increasing amount of aircrafts getting to end-of-life every year, the efforts and challenges to recover these enormous valuable products, and the importance of design as an attractive stage of product life-cycle to improve product recoverability at the end-of-life.

2.1 Aging worldwide air fleet

The growth in air fleet production has increased the number of end-of-life aircrafts annually. Back in 2007, it has been stated that there are more than 2000 civil aircrafts (excluding military aircrafts) grounded and are waiting for an appropriate end-of-life treatment (Towle, 2007). It has been also estimated that more than 250 aircrafts are going to be retired every year for the next two decades (Feldhusen *et al.*, 2011). Indeed, with the current increasing market growth and competition, airliners are getting more and more interested in purchasing new aircrafts with newer technology, higher passenger comfort, and lower utilization cost (i.e. fuel, and maintenance cost). In addition, to raise money in the capital markets, major aircraft lessors and financial institutions aim to keep the average age of aircrafts in their portfolios as low as possible.

Therefore, it is not far to expect that the actual units per year of retired aircrafts would be even much higher (up to 700 aircrafts per year including freighters) in compare with what was mentioned earlier (Boeing, 2013). Although this amount is small in compare to the one in automotive sector (it represents 0.4% of the number of cars reaching to end-of-life every year), the assets value of the materials and components in retired aircrafts is highly considerable depending on the technologies availability (Das and Kaufman, 2007; Asmatulu, Overcash, *et al.*, 2013; Camarsa *et al.*, 2013; Mascle, 2013b). Figure 2-1 represents the dramatically increasing amount of civil aircrafts getting to end-of-life over the next decades.

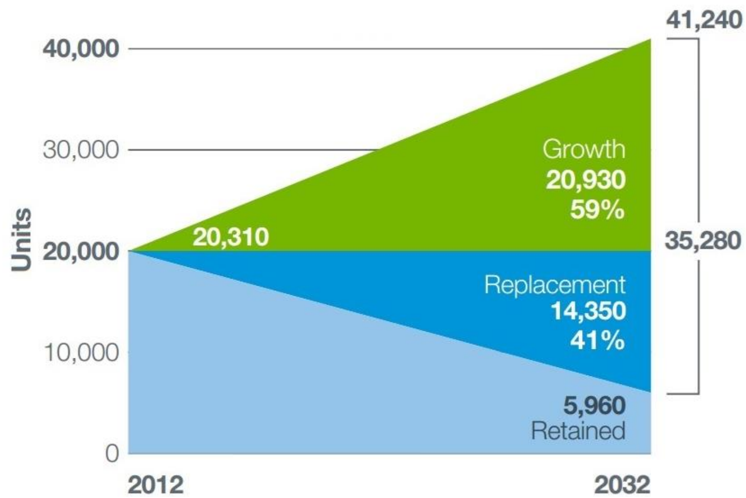

Figure 2-1 Increasing amount of fleets getting to end-of-life in the next years; retrieved from: (Boeing, 2013)

2.2 Product life-cycle and recovery

The development of a product starts with design which can be described as a set of decisions in order to solve a particular set of requirements for the product during its life-cycle (Benhabib, 2003; Deng *et al.*, 2009). The perception of life-cycle for a product is an overall inventory of all the stages and processes involved from "cradle" (raw material extraction) to "grave" (end-of-life). The generic layout for a product life-cycle is shown in Figure 2-2.

Raw material extraction is the process of retrieving materials of interest from the environment reservoirs. Gold, aluminum, and uranium, constitute some examples of materials with high extraction costs (environmentally and economically). Mostly, recycled materials are preferable to virgin materials. The extraction of virgin materials causes higher environmental disruption in compare to properly recycled materials. Less energy is required in a recycling process versus its counterpart for raw material extraction. Furthermore, recycling avoids material landfill/disposal.

Manufacturing a product involves the production processes and steps to be followed in order to turn the materials into parts/components. Depending on the product specifications, market needs, etc. the parts and manufacturing techniques can be quite diverse. Assembly is defined as the phase where components are joined and integrated via some manual or automated processes to build different product parts. The amount of steps involves in an assembly process is highly related to the complexity of the design varying from two to thousands of steps. Once the assembly process ends, the product is presented to the market. Packaging plays a critical role in guarantying product protection, providing information and simplifying storage, handling, and transportation. The use phase is referred to the period of time the consumer owns and operates the product. Depending on the product, different scheduled or unscheduled maintenance activities might be required to preserve the product performance and functionality. Energy consumption and waste generation during use and maintenance phase are the elements of interest for life-cycle inventory. Finally a product gets to end-of-life because of two main reasons: technology obsolescence and/or physical deterioration (Rose *et al.*, 2000; Xing *et al.*, 2003). End-of-life is the last but not the least phase in the product life-cycle that includes a subset of different strategies to recover (i.e. reuse, remanufacture, recycle, or incinerate) or dispose a retired product. Product recovery is also known as product rebirth (Mascle, 2013a).

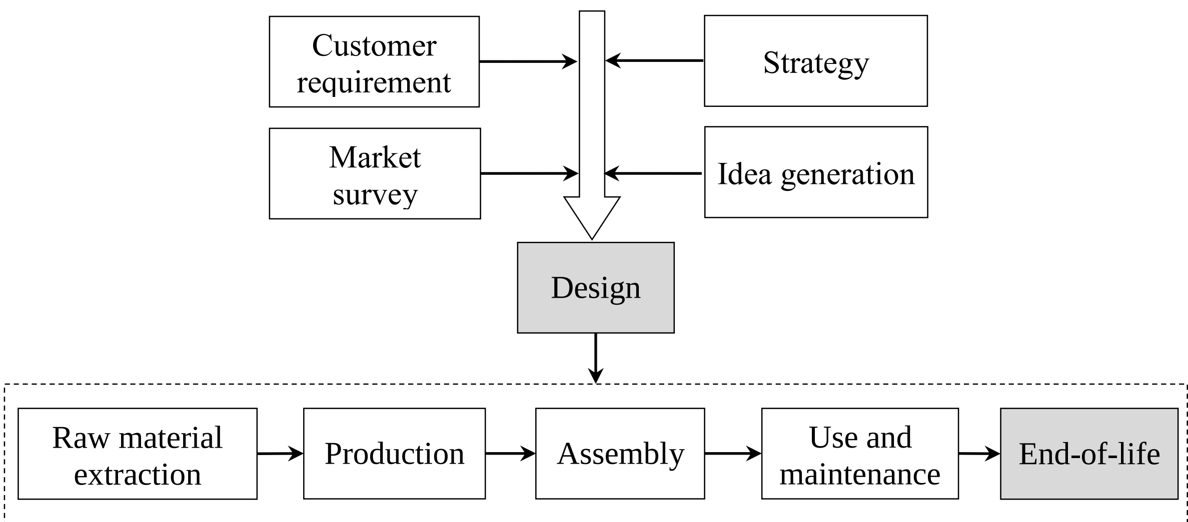

Figure 2-2 Generic stages involved in life-cycle of a product

These strategies have been described in the literature with different perspectives depending on the research focus (Masui *et al.*, 1999; Rose *et al.*, 2000; Xing *et al.*, 2003; Remery *et al.*, 2012; Mascle, 2013a). In our consideration, putting together the most common points among the definitions found in the literature, the concepts for end-of-life strategies are stated as follows:

Reuse: products or subassemblies are used "as is" directly in another application, usually the same as original application.

Remanufacture: a series of manufacturing steps (disassembly/assembly) in order to return a product or its subassemblies into "as new" condition or even with a better performance.

Material recovery: involves "material recycling" or "material valorization". Material recycling includes four types based on the state of material to be reprocessed. Primary: recycling in the original application; Secondary: recycling in a down-graded application (i.e. using the recycled aerospace aluminum in automotive industry due to inefficiency in retrieving the aluminum with original characteristics and desired purity); Tertiary: recycling plastics by decomposing their long molecule chains into basic monomers; Quaternary: incineration for producing heat and/or electricity. On the other hand, material valorization raises the value of the parts or subassemblies such that they would be used for another purpose (e.g. valorizing the vertical stabilizer to a fancy conference table).

Disposal: retired products are eliminated through landfilling or incinerating without any intrinsic value being retrieved.

The product end-of-life has increasing importance as a result of shortened product life-cycle and increasing awareness about the environment. Landfill and incineration treatment of waste result in severe environmental problems. Possible solutions to the challenge of end-of-life for products should tend towards reducing landfill, maximizing reutilization and controlling hazardous materials. In this regard, legislation communities come up with more and more strict regulations on products landfill and wastes disposal which have risen the fines for breaching environmental liability (González-Benito and González-Benito, 2006). In Europe since 2006 end-of-life policy for vehicles was set to: minimum 80% of the vehicle's material should be reusable and recyclable; and this ratio was supposed to increase to 95% by 2015 (Millet *et al.*, 2012; Blume and Walther, 2013).

Increasing profit is a main driving force to a company. The increasing costs of materials, energy, water and the production of other related auxiliary substances, make the manufacture of parts more expensive and therefore becomes a threat to company's profitability. A proactive recovery strategy provides a good opportunity for saving costs through reducing the size of material procurement, volume of component manufacturing and energy consumption. Therefore, recovery makes excellent business sense, because the market needs can be satisfied at lower costs and it adds extra value in terms of the "green image" for the company. A remanufactured car engine with the same functionality of a brand new engine can save 30 to 53% in terms of final price. This pricing is not considered as a negative sign of product quality, since the remanufactured engines are recertified and come with the same warranty (Smith and Keoleian, 2004; Liu *et al.*, 2005). In terms of market competitiveness, certainly all companies are working on upgrading their products to be more competitive in the market. Nowadays the market competition is very high so to count with green products is an undoubtable advantage (Ghadimi and Heavey, 2014). Therefore, companies may seek for passing from the passive environmental positioning, "Legislation Compliant" to be more active "Market Driven", or even proactive "Competitive Advantage" (Del Brío and Junquera, 2003).

In conclusion, Figure 2-3 shows that once a product retires from usage life to the end-of-life, it can have different looping options which are hierarchically: in-house reuse, product reuse/remanufacture, parts reuse/remanufacture, material recycle, and chemical/metallurgical recycle (Mascle, 2013a). The user is the focal point in the hierarchy. The left flow in the pyramid shows the sequential chain starting from material makers, part manufacturers, assemblers, until sellers. Once the product gets to end-of-life it follows another sequential chain going from collection centers to recycling infrastructures that are represented in the right flow of the pyramid. The middle nodes are the mediators (product renovation, component remanufacturing, and material recycling) that provide services in order to bring the product from the right flow back to the left. This logistic flow creates closed and open loops. The smaller are the loops, the less is the processing of materials and components for reapplication which leads to higher material use and energy efficiency.

2.2.1 Motivations for recovery in aerospace industry

Since the last decade, there is a need to impulse better environmental protection and responsible ways of dealing with natural resources in the field of aircraft end-of-life management. Before, there were no procedures to treat an end-of-life aircraft in a safe and environmentally responsible way. Once an aircraft retired from service, the spare parts were removed and re-introduced back to the market via scrap businesses or small maintenance companies. Circulation of bogus parts (uncertified parts in the second hand market), as well as uncontrolled disassembly/dismantling practices, were causing safety and regulatory concerns that needed to be addressed.

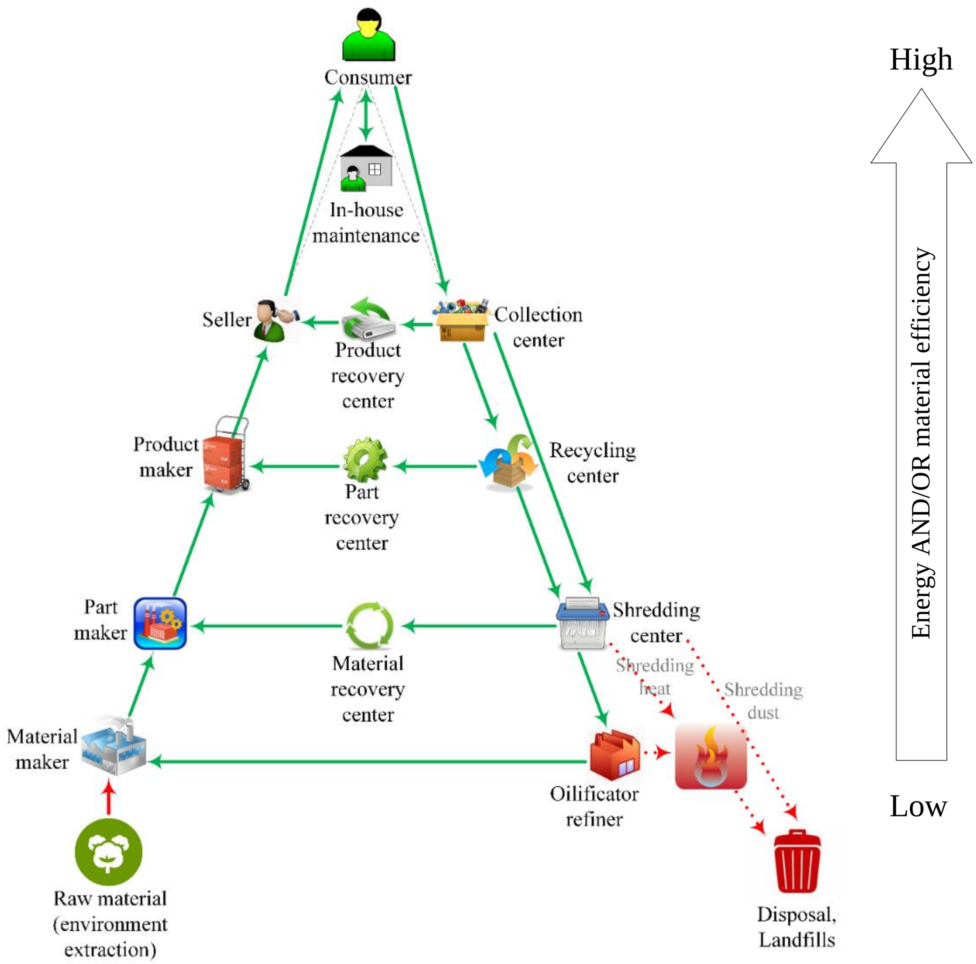

Figure 2-3 Theoretical product recovery hierarchy; redrawn from: (Mascle, 2013a)

With this aim, original equipment manufacturers (OEMs) requested aircraft dismantlers, parts re-distributors, materials recyclers, and research associations for a degree of control over aircraft end-of-life treatment (decontamination, disassembly, part-out, and recycling) to assist the aviation industry. Airbus and Boeing, the two major aircraft manufacturers, are the driving forces behind this movement.

In March 2005, Airbus initiated an experimental project on an A300-B4 aircraft called “Process for Advanced Management of End-of-Life Aircraft (PAMELA)” supported by European Union’s group LIFE (l’Instrument Financier pour l’Environnement). The project was founded with a budget of $3.3 million Euro. PAMELA was aimed to design an environmentally responsible process respecting the health and safety regulations that can be used to recover the increasing number of end-of-life aircrafts. The project lasted until November 2007 (Airbus, 2008b).

Afterwards, Airbus followed up another PAMELA project on an A380 in order to validate and scale up the methods for newer and larger aircrafts (Camarsa *et al.*, 2013). Although the methods and strategies employed are not publicly available, it was claimed that more than 85% of the weight of the aircraft can be recovered compared to the conventional rate of around 50%. This proof of concept demonstrated the potential to significantly reduce the wastes to landfill from 40-50% to less than 15%. As a result of this project, it was claimed that, by perfectly sorting materials the aluminum retrieved from the disassembly/dismantling process can be provided with the quality conforming to aviation specifications.

Airbus's efforts have been further reinforced by the establishment of Tarbes Advanced Recycling and Maintenance Aircraft Company (TARMAC Aerosave) at Tarbes airport, France, in 2009 (Airbus, 2009). TARMAC Aerosave brought together the refined experience from the original PAMELA projects as well as the expertise of Airbus group, SITA France (the leading company providing solutions for management and valuation of scrap), and SAFRAN group (one of the world's leading manufacturers of aircraft engines providing maintenance, repair and overhaul (MRO) services to airlines) to dismantle Airbus and non-Airbus aircrafts (Figure 2-4).

Figure 2-4 TARMAC Aerosave, Airbus's center of reference for end-of-life aircraft recycling; retrieved from: (Tarmac, 2016)

Boeing fleets in compare to Airbus are relatively older, thus a greater proportion of end-of-life aircrafts in the market carries the Boeing stamp. Boeing's objective for aircraft recycling is "Providing methods for safe parts recovery and environmentally responsible scrapping and recycling for airplanes that are not suitable for continued service" (Carberry, 2008).

Unlike Airbus, Boeing did not tackle the problem of aircraft recycling as a subject of research. Following its own foray into end-of-life aircraft recycling, in April 2006, Boeing founded a non-profit industry association called Aircraft Fleet Recycling Association (AFRA) in corporation with a group of 10 industry leaders. AFRA acts as a means of information exchange. AFRA has produced a "Best Management Practice (BMP)" document as a guideline in order to accredit companies on maintaining and reselling reliable aircrafts and returning them to service. Also, it accredits companies for safe parts removal, scrapping and recycling services for airplanes that cannot be returned to service (AFRA, 2016). Since then, AFRA has more than 60 members worldwide and it continues to grow. Corporate members range from aircraft manufacturers, engine OEMs, aircraft dismantlers and parts re-distributors, material recyclers, and finally research institutions (Table 2-1).

As an international consortium, AFRA is recognized as Boeing's key component for aircraft recycling objective. The mission is to pursue and promote environmental best practices, regulatory excellence, and sustainable developments in aircraft disassembly, as well as recovering and recycling aircraft parts and materials. AFRA membership is open to companies with businesses focused on world's aging air fleet, as well as university groups, research institutions, and technology companies that are developing enhanced aircraft recycling management and processes.

As a partner of AFRA, in 2011, Bombardier Aerospace in corporation with "Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ)" and other research centres and university groups, launched an aircraft recycling project. The project is called "Process for advanced management and technologies of aircraft end-of-life (CRIAQ-ENV412)". The project was involved in the disassembly/dismantling of a Bombardier Regional Jet aircraft at the Centre de Technologie Aéronautique (CTA) and the goal of the project was to ameliorate the existing managerial and technical methods in the field of end-of-life aircraft recycling. The research done in this thesis was performed within the framework of this project. This collaboration between academia and aviation industry is a valuable action to raise awareness and push forward the research toward an appropriate aircraft recycling.

Table 2-1 List of some AFRA-accredited members around the world

Main field of activity	Company name	Country
Aircraft manufacturer	Boeing	United States
	Bombardier Aerospace	Canada
	Embraer	Brazil
	Bell Helicopter Textron	Canada
Engine OEM	Rolls-Royce	United Kingdom
	Pratt & Whitney	United States
Disassembly/Parts re-distributor	Air Salvage International (ASI)	United Kingdom
	Aircraft End-of-Life Solutions (AELS)	Netherlands
	Aircraft Demolition	United States
	Rheinland Air Service	Germany
	Valliere Aviation Group	France
	Green Bird Aviation	Belgium
Materials recycler	Bartin Recycling Group	France
	Aviation International Recycling	Spain
	ELG Metals	United States
	Universal Recycling Company	South Africa
	Mesco Aerospace Limited	India
	Nantong Metalwell Co., Ltd.	China
Research institution	University of Nottingham	United Kingdom
	Oxford University/WINGNet	United Kingdom

2.3 Design aid tools for end-of-life

Design phase plays an important role in life-cycle of products. Approximately 70 to 90% of product’s life-cycle costs can be determined at the design phase through design choices, such as materials and manufacturing process selections (Erixon, 1998). This ratio might be less, depending on the type of product considered and the requirements for manufacturing (Ulrich and Pearson, 1993). An estimation done in an internal study by Ford is shown in Figure 2-5.

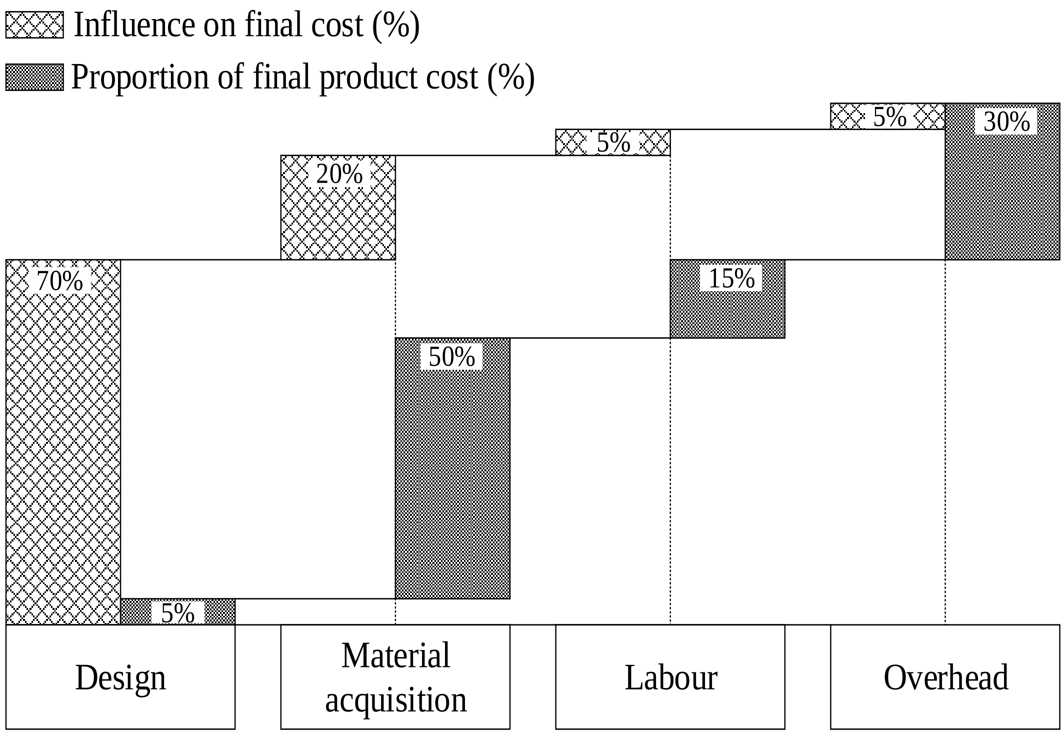

Figure 2-5 Influence of design on product life-cycle costs in automotive sector; redrawn from: (Erixon, 1998)

At the design phase, designers have substantial degree of freedom in determining the characteristics of the product. Even in the case that the technological concept already exist, there are many decisions still to be taken at the design phase such as product decomposition into components (e.g. make one big complex component or many simple components), how to attach those components together (e.g. screws, rivets, snap fits, or adhesive bonding), material selection (e.g. gold, aluminum, composites, or plastics), components manufacturing process (e.g. molding, machining, or additive manufacturing), etc.

To support the additional requirements of the product during its life-cycle, different design concepts ("Design for X") have been introduced. "Design for environment" has become an emergent concept to be included in the development of current products. With this perspective, the design performance should take into account environmental and social issues such as health and safety upon the whole product/process life-cycle. It is recommended to consider these environmental factors as earlier as possible before any manufacturing decisions are committed (Mascle and Zhao, 2008). Design for environment considers all the life-cycle phases of a product. End-of-life is the last phase of product life-cycle and is gaining more attention from companies in order to improve the recoverability of their products and reduce hazardous materials remaining in the environment (Rose, 2001).

The appropriate end-of-life strategy can be determined early in the product conceptual design counting with the fact that designers have a profound understanding of the product characteristics. According to Olivier Mavallon, director of the PAMELA project, the aircraft should be recyclable by design (Airbus, 2008a). In order to succeed with this statement, the design team should incorporate all the critical elements accumulated during the recycling project and convert them into documentations with the specific design requirements for aircraft end-of-life. There are studies that have tried to perfuse the end-of-life aspects of product directly into the design phase. ELDA (End-of-Life Design Advisor) has been described as the first methodology for product end-of-life management (Rose *et al.*, 2000). It was developed to be used at the early stage of design to predict the potential end-of-life strategy based on some product technical characteristics: "wear-out life", "technology cycle", "level of integration", "number of parts", "design cycle", and "reason for redesign". ELDA methodology is based on the statistical analysis and clustering algorithm for categorization, CART (Classification And Regression Tree). From thirty-seven case studies, the end-of-life strategy predictions suggested by ELDA, were 89% in agreement with the ones from industry best practices (Rose *et al.*, 2002).

A similar study was approached by Xing (2003) where it critically discussed some redundancies among the technical parameters considered by ELDA. For example "design cycle" does not need to be considered as an independent parameter since it is already included in "technology cycle" or "reason for redesign". Likely, the prediction of end-of-life strategy based on "number of parts" can be delivered by "level of integration" which by itself should be more focused on functional integration (conceptual design) of the product rather than physical structure (detail design) that was claimed by ELDA.

With this perspective, Xing (2003) introduced PEOLSP (Product End-Of-Life Strategy Planning) based on only four parameters. To deal with the uncertainty and vagueness in the nature of these parameters, the theory of fuzzy sets (Zadeh, 1965) was applied in PEOLSP. PEOLSP was applied to fifteen case studies and pretty much the same results (93.3%) were obtained in compare to the ones from ELDA. However, PEOLSP narrows the end-of-life strategies into three (“reuse”, “remanufacture”, or “recovery”), while ELDA predicts for five strategies (“reuse”, “reuse with service”, “remanufacture”, “recycle with disassembly”, or “recycle without disassembly”). The summary of these two methodologies are illustrated in Figure 2-6.

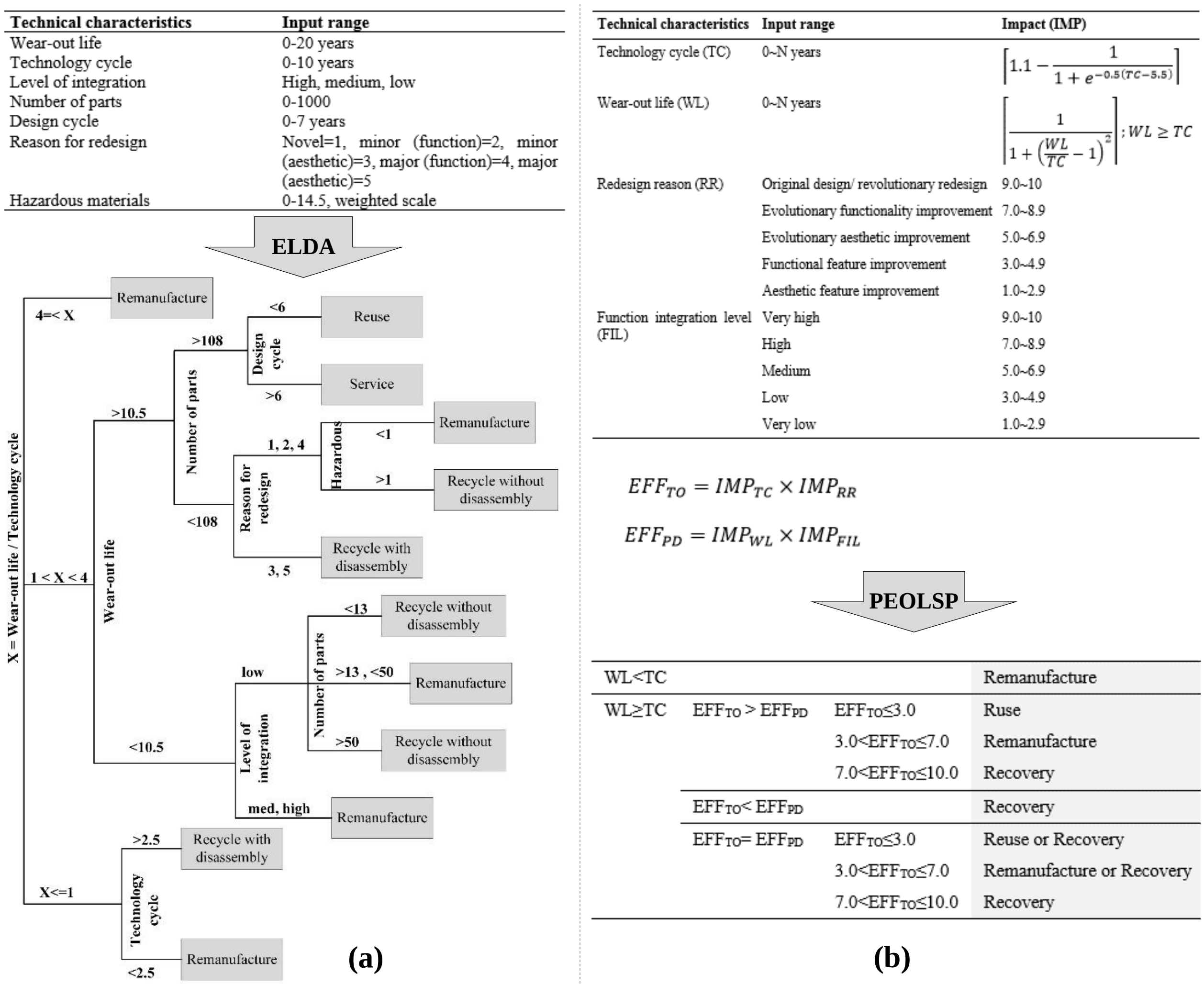

Figure 2-6 Methodologies to predict product end-of-life at design phase; *(a) End-of-life design advisor (ELDA)* (Rose *et al.*, 2000); *(b) Product end-of-life strategy planning (PEOLSP)* (Xing *et al.*, 2003)

Although these two methodologies were proposed for general products, in the case of more complex products, probably more refined parameters and techniques should be taken into account. For example, the "economical and social effect" can influence the customer satisfaction and worker's life and consequently the end-of-life strategy for the product (Mascle, 2013b).

ELSEM (End-of-Life Scenario Evaluation Method) is a methodology of new generation also to be used at the early stage of design for product end-of-life strategy prediction (Remery *et al.*, 2012). The best end-of-life strategy is ranked through a multi-criteria decision-making process based on fifteen technical attributes and six end-of-life strategies as alternatives ("reuse", "remanufacturing", "recycle with disassembly", "recycle without disassembly", "incineration", and "disposal"). Certainly, the relative importance weights and the number of attributes can be adjusted depending on the goals and preferences of the companies. The use of multiple attributes can lead to difficulty for data collection especially at early stage of design where some characteristics of the product are not fixed yet. Therefore, ELSEM employed linguistic variables (Zadeh, 1975) to alleviate the uncertainty associated to those parameters that are imprecise and subjective to measure. It is worth to mention that these methodologies can be applied either for a product as a whole and/or for different parts/modules of the corresponding product.

It is immensely rigorous and challenging the design of complex systems such as an aircraft or an aero-engine. Eres *et al.* (2014) presented a design methodology to capture customer needs at conceptual design in the case of aerospace industries. The value-driven design methodology was developed based on identifying all relevant stakeholders' needs throughout the extended aerospace enterprise (i.e. airlines, airports, society) (Monceaux *et al.*, 2014). A concept design analysis method was used to map these captured customer needs into engineering characteristics. Even though this design approach is not directly focused on aircraft end-of-life, it can be seen from the case studies presented that one of the customer needs is "green aircraft". End-of-life plays an important role for the green image of the aircraft and should be definitely considered as a high-level important customer need at the early stage of design (Keivanpour *et al.*, 2015).

2.3.1 Design for disassembly

The prediction of an appropriate end-of-life strategy is the first step in order to achieve a feasible design for end-of-life, since modules structure, material compositions, and fasteners selection are determined in accordance to the predicted strategy (Mascle, 2013b). However, in order to succeed with the end-of-life strategy predefined, disassembly plays a crucial role for all the alternatives. From engineering point of view, disassembly is known as the organized process of taking apart a systematically assembled product. Products might be disassembled not only when they reached to end-of-life for recovery purposes, but also for maintenance and serviceability during their life-time.

In general, two types of activities are involved in a disassembly job; value added and non-value added. Value added activities include the separation of parts and materials to enhance the value of the end-of-life product (i.e. reuse, recycle, etc.). On the other hand, loading/unloading, inventory, inspection, material and tools handling, and so forth are considered as non-value added activities. They do not create values to the end-of-life product meanwhile they must to be performed several times in a day which consume labor and equipment capitals. A research done by Kazmierczak *et al.* (2005) claimed that, only 30% of a disassembly work counts as value-added.

A disassembly process can be affected by some parameters such as operational environment, duration, labor proficiency, tools, methods, degree of precision required for effective tool placement, weight, size, material and shape of components being disassembled, etc. (Desai and Mital, 2003). An inefficient disassembly job brings additional cost to the end-of-life products' owners, and that is why in most cases they prefer to abandon their retired products instead of recovering them. Since, the desire is directed to increase the products recoverability by a facilitated disassembly work, a careful design with especial attention to disassembly is required.

In general, the disassembly process can be classified in two categories: "Non-destructive disassembly" for reuse purposes consists in safe removal of fasteners with the aim to retrieve the parts undamaged, with high quality and preserving the functionality; while for recycling, to preserve the functionality of the parts is not a main issue since the goal is to increase the material homogeneity only. On the contrary "destructive disassembly" refers to the use of brute force for taking apart the components by cutting, breaking, tearing, etc. (Kroll and Hanft, 1998). In this thesis, we refer "disassembly" as non-destructive disassembly and "dismantling" as destructive disassembly. Obviously, doing disassembly is more favorable to the environment than dismantling, since the intent is to keep the "intrinsic value" of the parts and materials almost intact. The intrinsic value depends on the end-of-life strategy (reuse, valorization, or recycling).

Design for disassembly is a concept directed to specifically evaluate the ease of disassembly of the components. Different approaches can found in the state of the art focused of design for disassembly. Güngör (2006) considered the selection of fasteners as an important feature for a suitable product disassembly at end-of-life. An analytic network process model was employed to evaluate and select the most appropriate connection type among different alternatives. Other studies have also focused on fastener selection using decision-making based methodologies (Jahau Lewis *et al.*, 1992; Ghazilla *et al.*, 2014; Jeandin and Mascle, 2016). Since many parameters can influence the disassembly job, only considering fastener selection might limit the design evaluation.

A quantitative method was introduced by Das *et al.* (2000) using a numeric disassembly effort index. The total operating effort to disassemble a product was estimated by a multi factor model. This model more than providing a detailed accurate cost, provides reliable inputs that can be used in disassembly related economic models and decision-making problems. Similarly, other studies have been concentrated on estimating disassembly on a time-based perspective (Kroll and Hanft, 1998; Desai and Mital, 2003). Desai and Mital (2003) proposed a methodology to estimate the disassembly time. Five disassembly parameters were taken into account and each parameter was subdivided into different categories that were assigned with time-based numeric scores. This allows to estimate the disassembly operation time for the components. A recent study integrated the two methodologies from Das *et al.* and Kroll and Hanft, where the results of the time based disassembly model (Kroll and Hanft) were used to estimate the disassembly effort (Harivardhini and Chakrabarti, 2016).

These studies considered different disassembly parameters with different goals applicable to small products handled by a seated operator. The disassembly operation has a dynamic nature depending on the “disassembly state” and certainly for more complex products this intrinsic characteristic cannot be neglected. Among the models revised in the literature, there is a lack for assessing the combination effects of the parameters in the disassembly job. For example, having two parameters “accessibility” and “connection type”, probably the mixed effect of these two parameters will influence differently the disassembly job versus each of them independently. Taking into account this fact, could provide a better understanding of the parameters for the team of design and lead to a more realistic disassembly model.

2.4 Aircraft end-of-life management

An aircraft gets to end-of-life not only because of end of its economic life but also due to high maintenance cost, damage beyond repair, a bankruptcy situation, or be used as a source to supply spare parts for worldwide air fleet. Once the aircraft goes out of service, it needs to be parked in certain conditions under some required inspections. This includes protection of interior furnishings, installation of humidity controllers, preservation of exposed metals, engine interval checks, rotating tyres, operational checks of aircraft hydraulic, electrical, and air conditioning systems, etc. For example to put an A320 aircraft into "in-storage" condition will cost the owner more than $15,000 USD. Additionally, interval checks for an in-storage aircraft need to be repeated at every 7 days, 15 days, 30 days and higher intervals. These small interval checks can cost $525, $1,100, and $2,500 USD, respectively (AFRA, 2015).

Depending on the condition of the aircraft, it can be reactivated for ferry flight or returned to service following the Aircraft Maintenance Manual (AMM) instructions. The reactivation process for an A320 can cost up to $21,000 USD. Since, the expenses associated to storing an out of service aircraft can increase quite rapidly, it is desired to disassemble/dismantle it shortly after its last flight. Storing an out of service aircraft to wait for an alternative use is not a viable long-term option (Mascle, 2013b; AFRA, 2015).

Aircraft end-of-life management involves three major phases: teardown evaluation, disassembly/dismantling, and parts/materials recovery (Figure 2-7). Prior to disassembly/dismantling of an aircraft, a teardown evaluation is required. Teardown evaluation includes a series of sales forecasts and review of "aircraft technical records" in order to establish the assets value. Technical records contain the history of all scheduled and unscheduled maintenance activities.

Up-to-date records are critical for full assets value evaluation and part extraction during the disassembly/dismantling phase. For some parts, such as engines, these records are required back to the point of manufacture. A questionable part with an unclear history and trace will have a potential impact on the resale of the part and serviceability of any future aircraft it is used on. If there are no associated maintenance records to an end-of-life aircraft, the only value remaining would be materials for recycling.

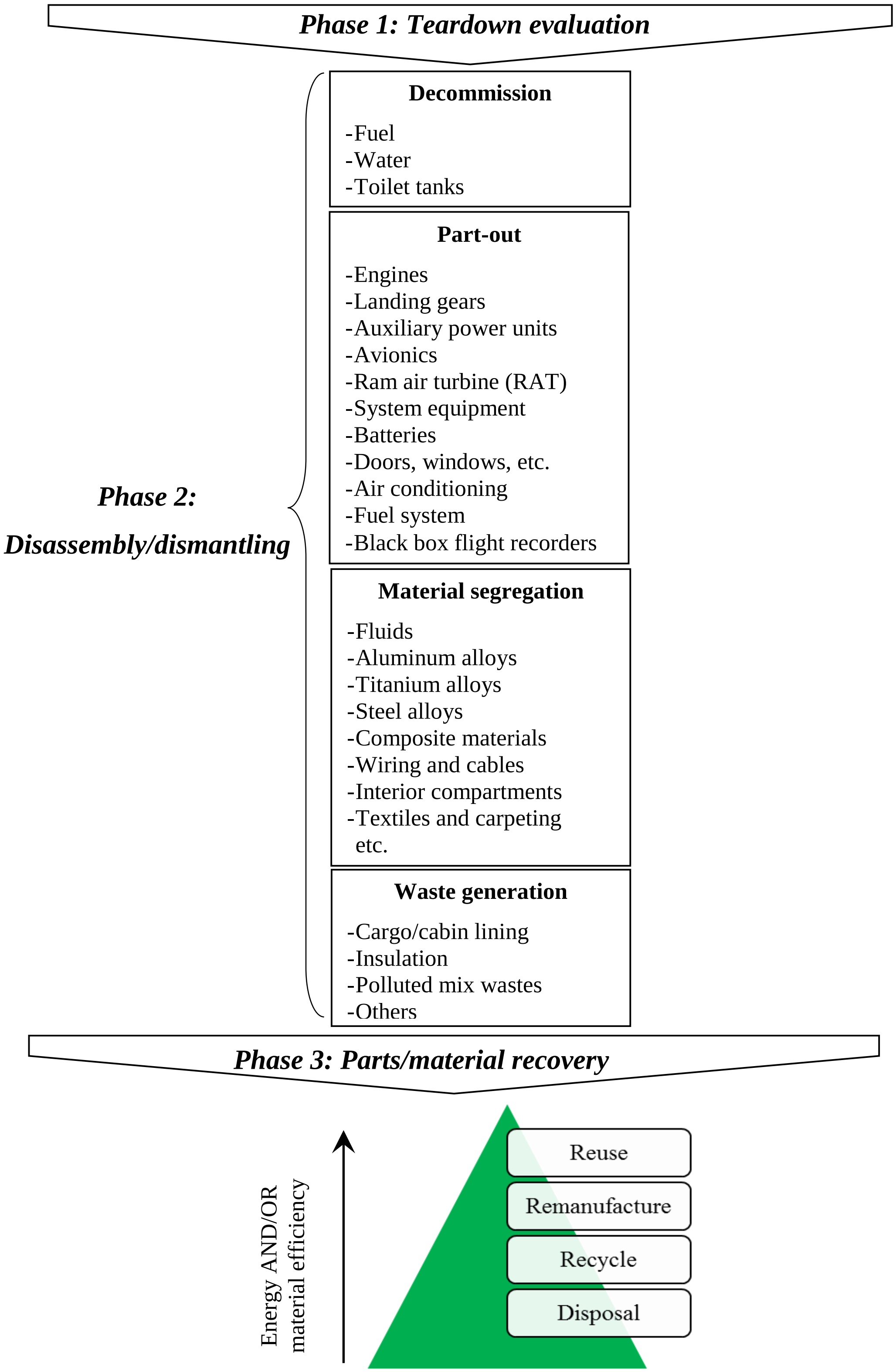

Figure 2-7 Aircraft end-of-life management approach

For example, Derk-Jan van Heerden, general manager at Aircraft End-of-Life Solutions (AELS), explains "a Boeing 737 parked at an airport with no technical records available, only has positive value left in the metal" (AFRA, 2015).

Components value also depends on where an aircraft type is in its life time, and size of the market. At a certain point suppliers will stop producing specific parts for aged aircrafts. This will generate a shortage of available spare parts for the older types over the time, affecting the prices of remaining stock and, therefore, increasing the potential teardown evaluation. On the contrary, if more of a specific type of aircraft has already been disassembled, then a substantial supply of spare parts would be available on the market, reducing the teardown value.

Therefore, the volume of parts removed from an end-of-life aircraft (for reuse/remanufacture) can greatly vary (from 200 up to 1,200 parts), depending on the aircraft type, condition, age, maintenance and technical records, market demand, etc. (Harbison, 2015). For instance, engines are the first part to be taken out of an end-of-life aircraft at a recycling facility for further use in another aircraft. In some cases, engines can make up to 80% of the value of an aircraft. The teardown value for engines is in direct relation with back-to-birth technical records, remaining engine flight hours (EFH) and engine flight cycles (EFC), previous modifications and repairs, market demand, etc. Consequently, the teardown value for the engines of a specific type of aircraft can vary from $80,000 to $1.25 million USD (AFRA, 2015). However, according to Mark Gregory, managing director at Air Salvage International (ASI), "in some cases you get more money for parts, rather than reselling the engine as whole" (Cacciottolo, 2011).

Due to the strict quality control systems in air fleet, all the parts that are removed from an end-of-life aircraft must have a certain quality in order to be reused/remanufactured. Therefore, during the part removal, the end-of-life aircraft is treated as if it is under maintenance procedure until all the parts to be returned to the supply chain are removed. Accordingly, the disassembly of those parts should comply with relevant reference manuals (i.e. AMM and Illustrated Parts Catalogue (IPC)) (AFRA, 2016). In this regard, some researchers focused on developing models based on AMM in order to reduce the displacement in working zones during the disassembly job on an aircraft (Camelot *et al.*, 2013; Dayi *et al.*, 2016). Once all required components and reusable parts from an aircraft have been removed, the remaining airframe material will be scrapped and returned to the supply chain as raw material, or disposed in a landfill.

2.4.1 Material pre-sorting

Aircrafts are composed of different advanced materials including ferrous/non-ferrous metals (aluminum, titanium, steel, nickel, copper, etc.), carbon/glass/Kevlar fiber composites, wires, textiles, fluids, wood, plastics, foams and insulations, etc. Excellent environmental benefits come out from recycling high-tech aerospace material rather than production from virgin materials (Asmatulu, Overcash, *et al.*, 2013; Eckelman *et al.*, 2014). However, the conventional management systems, technology, and knowledge for aircraft end-of-life and recycling are not sufficient and responsive to deal with the increasing amount of retired aircrafts every year.

A recent study performed in aircraft manufacturing facilities in Wichita, showed that only 20% of the potential recoverable materials from 1765 aircrafts was actually recovered (Table 2-2) due to some limitations such as lack of design, training, awareness, etc. (Asmatulu, Overcash, *et al.*, 2013). Meanwhile, it is claimed that, by taking the advantage of industry expertise and new technologies, the aircraft recoverability rate can be up to 85 to 95% of the weight (Airbus, 2008b; Carberry, 2008). Therefore, innovative and transdisciplinary management strategies should be encouraged (Keivanpour *et al.*, 2013).

Table 2-2 Total potential recyclable and actual recycled materials from aircraft manufacturing facilities in Wichita in 2009; source: (Asmatulu, Twomey, *et al.*, 2013)

Recyclable aircraft material	Potential recyclable material (kg/yr)	Actual recycled material (kg/yr)
Aluminum (different grades)	11,142,988	2,228,598
Ferrous metal (steel)	1,528,682	305,736
Oil (all types, from sources like engines, hydraulics, etc.)	754,017	150,803
Nonferrous metals (non-aluminum)	741,790	148,358
Composites	616,817	43,363
Electronics	15,429	3,086
Coated wire	8,954	1,791
Tires	5,445	1,089
Total	14,814,122	2,882,824

Shredding is a pre-recycling method conventionally used by aircraft dismantlers/recyclers that allows transforming huge components of the aircraft into smaller and more practical dimensions. Crushing the carcass as a whole piece, results in a soup of different materials. Table 2-3shows that the income value obtained from mixed material is only 27% of the actual price that can be recuperated from pre-sorted materials. To treat this co-mingled scrap, recyclers need to employ different separation techniques (i.e. magnetic separation, air separation, eddy current separation, sink float/heavy media, color sorting, and spectrographic) in order to classify a relatively pure material scrap streams prior to sending to recovery channels (Bell *et al.*, 2003). This physical separation will make materials recycling process easier, and leads to products of high quality for direct resale back into the market. A typical physical separation sequence is shown in Figure 2-8. The technologies used and their use sequence varies between different secondary producers and scrap processors (Gaustad *et al.*, 2012).

Table 2-3 Income from reselling of metals for an Airbus A310-300; source: (Dubé and Bélanger-Gravel, 2011)

Aircraft material	Weight (kg)	Price (USD/tonne)	Price for sorted material (USD)	Price for co-mingled scrap (USD)
Aluminum (different grades)	54,795	$1,990	$109,042	
Ferrous metal (mostly steel)	13,191	$515	$6,793	
Titanium	6,088	$27,000	$164,376	
Copper	2,029	$7,500	$15,218	
Others (composites, electronics, glass, plastics, rubber, wood, isolation foam, etc.)	N/A	N/A	N/A	
Total	76,104	-	$295,429	$79,110

2.4.2 Aerospace aluminum recycling

To an end-of-life aircraft, aluminum remains as the most attractive material for recycling. High strength-to-density ratio, corrosion resistance, and weight efficiency are some mechanical properties that make the aluminum to be widely used, especially in compressive designs (Davis, 1999). A typical aircraft is composed of 65% to 77% different aluminum alloys depending on the aircraft type (Perry, 2012; Asmatulu, Overcash, *et al.*, 2013). This ratio might be lower in newer aircraft due to the use of composite materials; but still aluminum remains as the most abundant metal in the airframe.

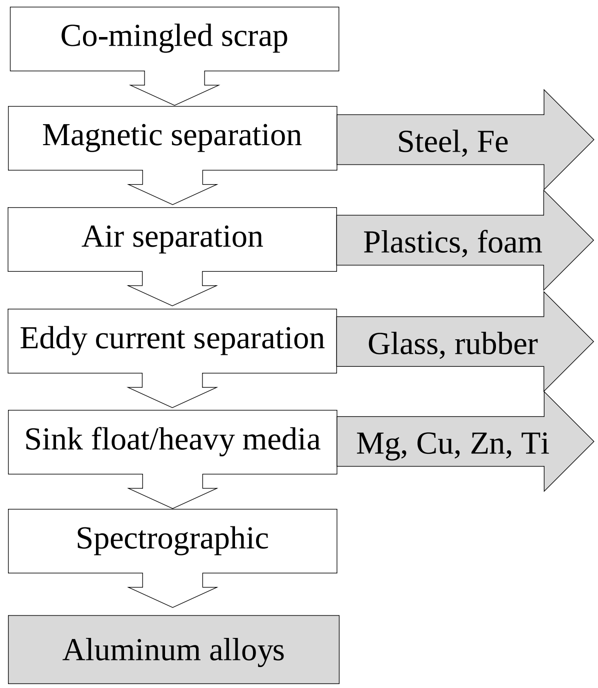

Figure 2-8 General diagram of possible physical separation techniques and their sequence for co-mingled scrap; source: (Gaustad *et al.*, 2012)

Aluminum recycling brings several environmental and economic benefits. Compared to other materials, aluminum production has one of the largest energy differences between primary and secondary production (i.e. producing it by recycling) (Gaustad *et al.*, 2012). The production of aluminum as secondary metal requires only about 2.8 MJ/kg of metal produced while primary aluminum production requires about 17 times more. This 94% energy saving is a powerful economic incentive. In terms of the environment, production of secondary aluminum leads to a significant reduction of CO_2 emission in comparison to primary aluminum (Table 2-4) (Grimes *et al.*, 2008).

With these energy and cost savings, it is highly advantageous for manufacturers to maximize the usage of secondary material in their products. Even though basic aluminum alloys from packaging and automotive applications have been widely commercialized, in the case of hi-tech aerospace aluminum is not the same scenario. These specialized alloys have less market demand and to achieve their mechanical properties requires more complex production processes while the cost-effectiveness performance is questionable (Das and Kaufman, 2007; Latremouille-Viau *et al.*, 2010).

Table 2-4 Primary versus secondary aluminum production; source: (Grimes *et al.*, 2008)

Element	Primary aluminum (per kg)	Secondary aluminum (per kg)	Ratio (Primary:Secondary)
Energy (total)	47 MJ	2.4 MJ	17:1
CO_2	3.83 kg	0.29 kg	13:1

Among all aluminum alloys, aerospace alloys are the most highly alloyed and expensive ones (Das *et al.*, 2008). To a large extent, aircraft alloys fall into two alloy series of 2xxx and 7xxx series of wrought alloys. In compare to cast alloys, wrought alloys have lower tolerance to impurities (Das and Kaufman, 2007). The major alloying elements used with aluminum are Silicon (Si), Iron (Fe), Copper (Cu), Manganese (Mn), Magnesium (Mg), Zinc (Zn). The total amount of these elements can constitute up to 10% of the alloy composition. The composition elements of some alloys used for many years in aircraft structures are shown in Table 2-5.

Table 2-5 Composition elements of some 2xxx and 7xxx aluminum alloys; source: (Davis, 1999)

Alloy	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Zn (%)	Aluminum (%)
2014	0.5-1.2	1.0	3.9-5.0	0.4-1.2	0.2-0.8	0.25	Remainder
2024	0.50	0.50	3.8-4.9	0.3-0.9	1.2-1.8	0.25	Remainder
2214	0.5-1.2	0.3	3.9-5.0	0.4-1.2	0.2-0.8	0.25	Remainder
2124	0.20	0.3	3.8-4.9	0.3-0.9	1.2-1.8	0.25	Remainder
2324	0.10	0.12	3.8-4.4	0.3-0.9	1.2-1.8	0.25	Remainder
7050	0.12	0.15	2.0-2.6	0.10	1.9-2.6	5.7-6.7	Remainder
7075	0.40	0.50	1.2-2.0	0.30	2.1-2.9	5.1-6.1	Remainder
7175	0.15	0.20	1.2-2.0	0.10	2.1-2.9	5.1-6.1	Remainder
7178	0.40	0.50	1.6-2.4	0.30	2.4-3.1	6.3-7.3	Remainder
7475	0.10	0.12	1.2-1.9	0.06	1.9-2.6	5.2-6.2	Remainder

2xxx: “Alloys in which Cu is the principal alloying element, although other elements, notably Mg, can be specified. 2xxx series alloys are widely used in aircraft where their high strengths (yield strengths as high as 455 MPa) are valued” (Davis, 1999).

7xxx: “Alloys in which Zn is the principal alloying element. They are mainly used in aircraft structural components and other high-strength applications. The 7xxx series are the strongest aluminum alloys, with yield strengths higher than 500 MPa” (Davis, 1999).

As was mentioned above, these aerospace alloys contain relatively high levels of Cu and Zn, among others which make the recycling process more complex for reuse in aerospace applications. Furthermore, no or negligible levels of impurities should be contained into aircraft alloys with the aim to optimize performance characteristics like fracture toughness and corrosion resistance. Therefore, nowadays, in order to meet the requirements of aerospace alloys and product specifications, most alloys are produced using primary metal.

In recycling the carcass, depending upon the rigorousness of the discrimination process during pre-sorting, a variety of different alloy compositions may occur. According to the literature, it is desirable at least to separate the 2xxx and 7xxx series alloyed components prior to recycling (Bell *et al.*, 2003; Das and Kaufman, 2007; AFRA, 2015). The estimated potential nominal compositions for 2xxx and 7xxx series alloys recycled separately are tabulated in Table 2-6. The same table also shows, the recycled metal composition of the alloys which cannot be pre-sorted before melting (it was assumed approximately equal amount of 2xxx and 7xxx alloys).

Table 2-6 Potential nominal compositions of some recycled aerospace alloys with and without segregation and pre-sorting; source: (Das and Kaufman, 2007)

Case	Recycled alloy	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Zn (%)	Others (%)
Sorted	R2xxx	~0.5	~0.5	~4.4	~0.7	~1.0	~0.2	~0.2
	R7xxx	~0.5	~0.4	~2.0	~0.2	~2.5	~6.0	~0.2
Co-mingled	R2xxx+7xxx	~0.4	~0.4	~3.0	~0.4	~1.8	~3.0	~0.3

In case of successful pre-sorting the 2xxx and 7xxx series, there would be chances to upgrade the recycled R2xxx and R7xxx in a 2024-like and 7075-like alloys, respectively. These alloys might be used in non-fracture-critical aerospace components or in non-aerospace applications such as railroad vehicles and truck structures. On the contrary, if the metals are not segregated, the composition of the alloy obtained does not match with any existing registered alloys. Therefore, if this new alloy is going to be used for any application, even castings, some curative post-processing steps are likely required, which can be complex, costly, and laborious (Das *et al.*, 2008; Gaustad *et al.*, 2012).

It is highly attractive to take the maximum advantage from pre-sorting techniques prior to recycling. The conventional physical separation techniques do not satisfy the pre-sorting of aluminum with different grades. Therefore, over the past years, some innovative techniques have been developed specifically for automated pre-sorting aluminum alloys such as: “Color sorting” and “Laser Induced Breakdown Spectroscopy (LIBS)”.

In Color sorting the metallic pieces are detected based on their color by computer image analysis. If the color of the pieces falls within a specified range, they will be automatically directed out of the material stream. This type of sorting can be achieved because when each aluminum series are put through a specific chemical treatment (etching), a unique color appears. For instance, aluminum high in Si and Mn will become gray while Zn and Cu combine to turn the piece dark. When the scrap flux reacts with a mild caustic or sulfuric acid solution, the 2xxx, 3xxx, and 7xxx alloy series can be sorted out. The use of other chemicals such as copper sulfate and hydrochloric acid allows to separate alloys 5xxx and 6xxx series (Schultz and Wyss, 2000). However, color sorting based techniques are not capable of separating alloys from the same family. Even though the principles for this sorting technique have been used in industry for many years, there are some limitations such as heat treating and the fact that the time from etching to rinsing the material can lead to variability in the color (Bell *et al.*, 2003).

The technique LIBS raised from the necessity to separate the aluminum alloys more accurately based on their chemical compositions. In LIBS technique, the piece of alloy scrap is bombarded by a pulse laser after being detected by a sensor. The laser hits the metal surface and produces an atomic emission. The chemical composition of the material is obtained by a spectrometer. The polychromator provides an optical spectra that is translated to a sorting signal. A mechanical device is activated via the sorting signal, placing the identified piece in a particular sorting container (Gesing and Harbeck, 2008). Considering that the pulse laser cannot penetrate deep into the metal surface, at the time of reading, the scrap pieces should be free of corrosion, lubricants, paints, and other coatings to avoid erroneous sorting. It has been recommended to employ color sorting prior to LIBS, in order to separate bare aluminum from coated aluminum. As shown in Figure 2-9, coated aluminum will go through a decoating procedure beforehand (Bell *et al.*, 2003).

Huron Valley Steel Corp. is the company that developed and implemented these techniques for aluminum alloy scrap sorting. They have developed a pilot-plant and it has been claimed that the first industrial alloy sorter will have a high throughput capacity to analyze and sort up to 100 million pounds of aluminum scrap per year (Gesing *et al.*, 2013). However, this may not satisfy the approximated 2.4-3.2 billion pounds of aluminum used annually in aerospace applications (Das, 2006).

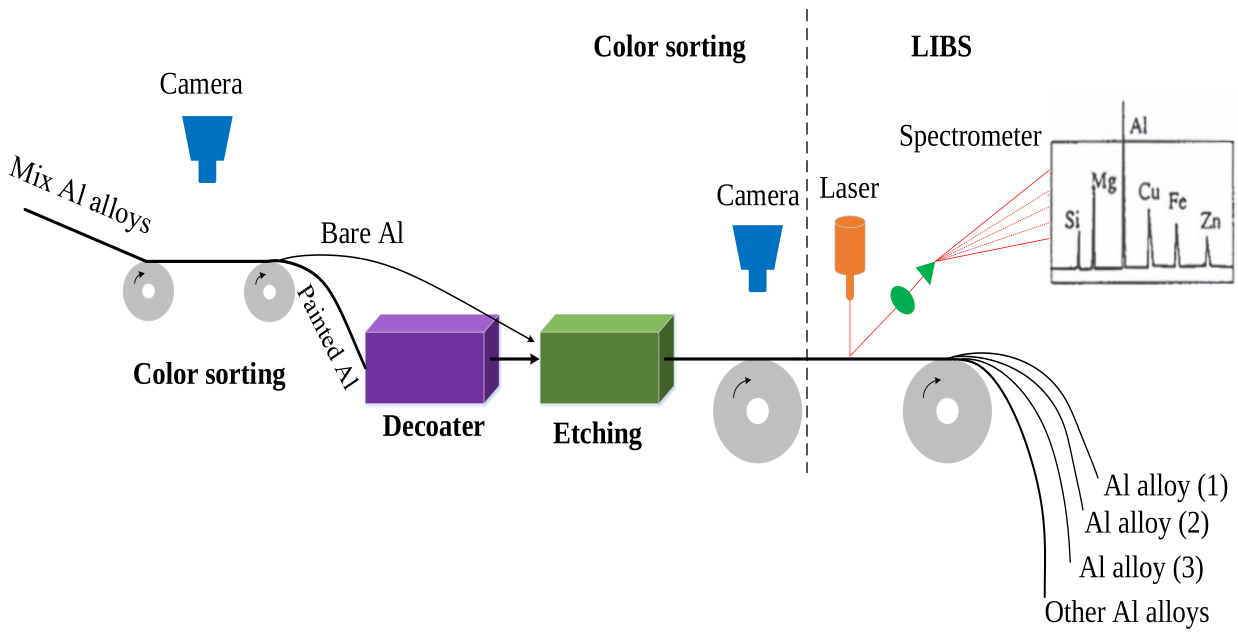

Figure 2-9 Color sorting and laser induced breakdown spectroscopy (LIBS) techniques for sorting different aluminum alloys

Although, these automated scrap sorting techniques will undoubtedly work after shredding, it is preferred to do as much segregation as possible at earlier stage (Gesing and Harbeck, 2008). Therefore, it seems practical to disassemble/dismantle the aircraft into certain logical component groups made from similar series of alloys (Das and Kaufman, 2007; Eckelman *et al.*, 2014; Mascle *et al.*, 2015). Moreover, these separations permit to remove the non-aluminum components before shredding.

2.4.3 Cost-benefit associated to disassembly/dismantling

As mentioned earlier, disassembly is the act of separation, and separation is acquired when the joints for the two components are clearly removed. A rigorous disassembly can be laborious and time-consuming, but is the best way to avoid cross contamination of different materials for recycling purposes. On the other hand, the action of cutting is to make an opening or incision in (something) with a sharp-edged tool or object. In terms of dismantling operations, cutting has been commonly used. However, cutting parts usually implicates that a certain portion of material X will be mixed with a higher concentrated material Y.

An interesting work performed in end-of-life vehicle sector, compared shredding with manual disassembly/dismantling (Tasala Gradin *et al.*, 2013). For shredding, the vehicle was grinded into small fragments and the co-mingled scrap was separated using automated physical separation methods (Figure 1-8). The issue with this strategy was that the 27% of the weight comes out as shredder residual which is a mixture that not only contains combustible materials (paper, wood, rubber, foams, polymers, etc.) but also glass, sand, dirt, and metal fractions. Consequently, this mixture is non-suitable for "incineration with energy recovery" and ends up to landfill. On the other hand, the manual disassembly/dismantling of the vehicle resulted in only 15% residuals from which 10% could be used for energy recovery by incineration and only 5% discharged to landfill (Figure 2-10). The life-cycle analysis on both strategies revealed that disassembly has a positive impact on climate change and metal depletion (Tasala Gradin *et al.*, 2013).

However, there can be a significant cost associated to product disassembly/dismantling. A study done by Ferrão and Amaral (2006) on vehicles manufactured in 1998 and before, showed that although increasing dismantling rate can improve the recyclability, disassembly/dismantling rate more than 14% of the weight is not economically viable. The efforts put in proper disassembly/dismantling in automotive sector does not pay off due to the market value of the recovered materials. Certainly, in aerospace industry is not the same scenario since the materials used in aircrafts are much higher valued; and the homogeneity of the materials retrieved from the recovery process can make a significant impact on their resale price.

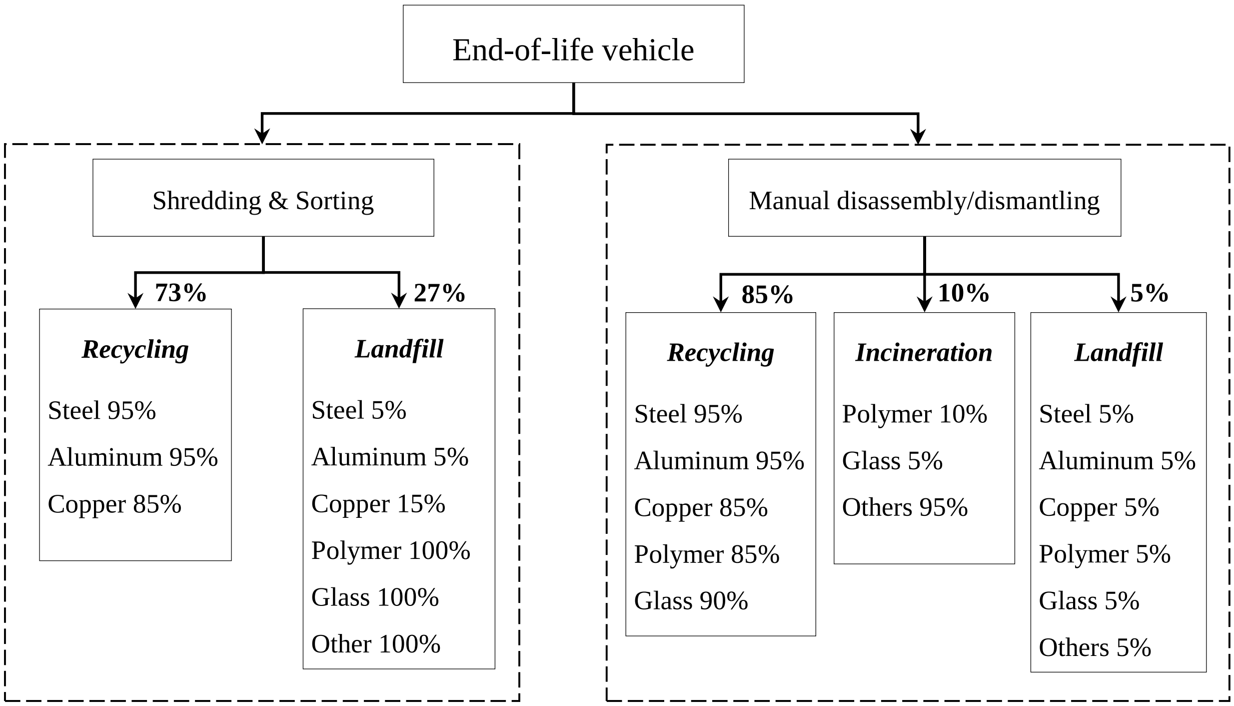

Figure 2-10 Benefits of disassembly/dismantling versus shredding for end-of-life vehicle; source: (Tasala Gradin *et al.*, 2013)

Two main parameters are involved into a recovery process: Recycling and Disassembly/dismantling (Feldmann *et al.*, 1999). The cost-benefit curves were plotted in function of material homogeneity to represent the behavior of these two parameters (Figure 2-11). The function curve of recovery process (in red) was obtained by summation of the curve functions for recycling and disassembly/dismantling. Increasing the homogeneity of the materials, the cost-benefit ratio for recycling decreases while, the one for disassembly/dismantling increases. To have a higher material homogeneity more disassembly/dismantling efforts will be imposed into the recovery process. The goal of implementing different strategies is to find the optimum strategy with the lowest cost-benefit ratio for the recovery process.

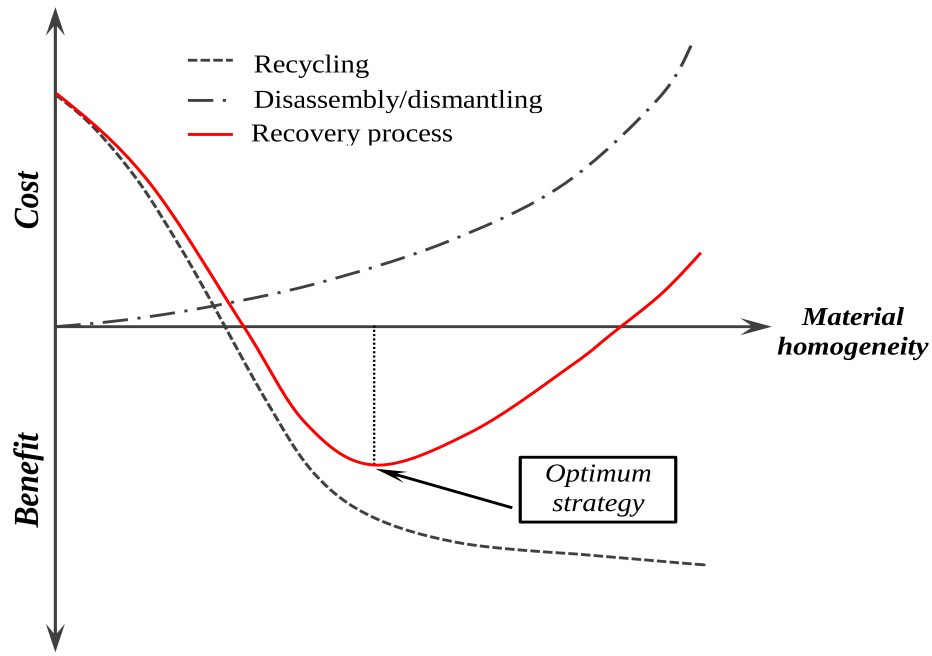

Figure 2-11 Schematic representation of the cost-benefit associated to a recovery process

CHAPTER 3 ARTICLE 1: EVALUATION OF PRODUCTS AT DESIGN PHASE FOR AN EFFICIENT DISASSEMBLY AT END-OF-LIFE

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3.1 ABSTRACT

Despite aerospace industries are moving toward circular economy and reutilization of materials and components, every year hundreds of aircrafts end up in landfills without an appropriate treatment. This is mainly due to the lack of a proper design for end-of-life. New innovative approaches should be considered at the design phase with remarkable attention to disassembly aspect at the time of retirement. Considering disassembly as a multi-criteria decision-making problem, several parameters may influence the performance of a disassembly-task. Taking the experience accumulated during the disassembly work on a Bombardier Regional Jet aircraft, five parameters were considered in this study. A hybrid design of experiment (DOE) and TOPSIS method was proposed in order to obtain a unique discriminant disassembly model to calculate the disassemblability index for each two given components. The results from ANOVA showed that the derived disassembly model has a 94.30% of reliability. The application of the proposed model at the design phase could facilitate the evaluation of disassembly operation at the end-of-life.

Keywords: Disassembly model; Design for end-of-life; Aircraft; Decision-making; TOPSIS; Design of experiment

3.2 Introduction

As a result of shortened product life-cycle and increasing awareness about the environment, legislation communities come up with more and more strict regulations for product manufacturers. In Europe since 2006 end-of-life policy for vehicles was set to: minimum 80% of the vehicle's material should be reusable and recyclable; and this ratio is supposed to increase to 95% by 2015 (Blume and Walther, 2013; Millet et al., 2012). In aerospace industry, according to Airbus (2008)'s report "Process for Advanced Management of End-of-Life of Aircraft (PAMELA)", around 85% of the weight of a civil aircraft can be potentially recovered (15% for direct reuse, and 70% through valorization). However, a recent study performed in aircraft manufacturing facilities in Wichita, showed that only 20% of the potential recoverable materials from 1765 aircrafts was actually recovered (Asmatulu et al., 2013b).

Many efforts have been done to increase the actual recoverability rate of aircrafts (Asmatulu et al., 2013a; Das and Kaufman, 2008; Feldhusen et al., 2011; Latremouille-Viau et al., 2010; Mascle et al., 2015). The researches have been focused on two main branches: improvement of end-of- life treatment methods and amelioration of product design at the development phase.

Looking at the efforts to improve end-of-life treatment techniques, in earlier attempts within the framework of the project "*Process for advanced management and technologies of aircraft end-of-life*" (CRIAQ-ENV412), different disassembly/dismantling strategies were implemented on a Bombardier Regional Jet aircraft with the aim to select the best strategy in terms of sustainability. The results showed that disassembly-based strategies can provide more environmental contributions (Sabaghi et al., 2015a). However, due to complexity in structure of the carcass, a complete disassembly is not economically viable (Sabaghi et al., 2015b). Somehow, this is due to the fact that current aircrafts are being conceived neglecting an efficient design for end-of-life.

Amelioration of product design at the development phase stands as a very promising approach to increase the product recoverability rate (Duflou et al., 2008; Giudice and Kassem, 2009). Several design methodologies have been proposed to be applied for end-of-life suitability such as: design for modularity, design for recycling, design for environment, design for disassembly, design for rebirth, etc. (Åkermark, 1997; Collado-Ruiz and Capuz-Rizo, 2010; Huang et al., 2012; Mascle, 2013; McCluskey et al., 2009; Qian and Zhang, 2009; Rose et al., 2000; Tseng et al., 2008). The productivity associated with all these design methods depends on a proper disassembly which leads to a higher rebirth rate for components and modules.

Nomenclature

ANOVA	analysis of variance
DOE	design of experiment
MCDM	multi-criteria decision-making
TOPSIS	technique for order preference by similarity to ideal solution
P1	accessibility
P2	mating face
P3	tools type
P4	connection type
P5	quantity and variety of connections
CR	consistency ratio for comparison-matrices
D	decision-matrix in TOPSIS
n	number of disassemblability parameters in decision-matrix D
m	number of disassembly-tasks (alternatives) in decision-matrix D
P_j	parameter j in decision-matrix D
A_i	disassembly-task (alternative) i in decision-matrix D
d_{ij}	input value of parameter j for disassembly-task i in matrix D
R	normalized decision-matrix
r_{ij}	normalized value of parameter j for disassembly-task i in matrix R
V	weighted-normalized decision-matrix
v_{ij}	weighted-normalized value of parameter j for disassembly-task i in matrix V
W_j	relative importance weight of parameter j
v_j^+	the best value for parameter j among the alternatives in matrix V
v_j^-	the worst value for parameter j among the alternatives in matrix V
PIS	positive ideal solution
NIS	negative ideal solution
d_i^+	Euclidean distance of disassembly-task i to PIS
d_i^-	Euclidean distance of disassembly-task i to NIS
RC_i	disassemblability index of disassembly-task i
Y	response-vector of disassemblability indices in DOE-TOPSIS model
X	coded decision-matrix in DOE-TOPSIS
β	coefficient-vector
β_0	Y-Intercept coefficient
β_j	effect coefficient of parameter j
ε	error-vector
$\hat{Y}$	predicted value of disassemblability index
X_j	coded input value for parameter j
p_j	un-coded input value for parameter j
$p_j(min)$	minimum possible input value (un-coded) for parameter j
$p_j(max)$	maximum possible input value (un-coded) for parameter j

Disassembly appears as an inevitable activity for products not only at the end-of-life but also during the products life time and maintenance (Das et al., 2000; McCluskey et al., 2009). Moreover, disassembly job cannot be seen as a static process since the disassemblability of the components may vary through the process depending on the “disassembly state”. Several works emphasized the importance of this aspect in evaluation of the components disassemblability for product redesign and disassembly sequencing (Das et al., 2000; Giudice, 2010; Lambert, 1997; Suga et al., 1996; Viswanathan and Allada, 2001).

Currently, there is a lack of a dynamic model that allows designers to efficiently assess the relationships among the components/modules in terms of disassembly at the development phase. In this work, disassembly was considered as a multi-criteria decision-making (MCDM) problem. Different disassembly parameters and their interactions were taken into account. A novel disassembly scoring model using a hybrid technique that combines Design of Experiments and Technique for Order Preference by Similarity to Ideal Solution (DOE-TOPSIS) was developed. The model allows to independently determine the difficulty index for every disassembly-task involved in the product disassembly. The model was developed under the project CRIAQ-ENV412 based on the accumulated experience in disassembly during the work on the carcass of a Bombardier Regional Jet aircraft.

Including this introduction, Section 3.3 presents the disassemblability parameters; in Section 3.4, are provided the preliminaries and the proposed methodology; the application of DOE-TOPSIS is presented in Section 3.5; validation of the model is given in Section 3.6; and finally, Section 3.7 presents the conclusion.

3.3 Disassemblability parameters

Disassembly-task is specifically defined as the act of separation. Separation is achieved when the mechanical connections such as fasteners, jo-bolts, rivets, i-locks, adhesive bonding, etc. for two components are clearly removed. Products are composed of different components assembled via different type of joints in an organized structure. Therefore, to disassemble a product, several disassembly-tasks might be required. These tasks would vary in terms of difficulty related to each one. The level of difficulty associated to a disassembly-task is referred as disassemblability.

Different qualitative/quantitative parameters can influence the disassemblability of the components. These parameters may differ from one product to another. Based on the established parameters, a model can be developed at the design phase to evaluate the disassemblability index for components in the product. Therefore, identifying the appropriate disassemblability parameters, provides more reliability to the model and is the most important and time consuming step.

After group meeting with the partners and decision-makers in the project CRIAQ-ENV412, a list of different disassemblability parameters was obtained. This process of knowledge extraction from the experts was performed using pseudo Delphi[1]. Having presented the problem and the importance to have a universal disassembly model, the group converged towards parameters with controllable characteristics at the design phase. Therefore, parameters such as: labor proficiency, workplace condition, material erosion, level of tools efficiency, rules, regulations, and standards, etc. were defined as uncontrollable factors and were not considered. Thus, based on the literature (Table 3-1) and the experience of the experts, the selected parameters are summarized as in Table 3-2.

Accessibility (P1) is a key factor in performing a disassembly-task. It is the measure of easiness (degree of freedom) to access to each connection. Accessibility can be determined by dimensions and locations of the connections to be removed. For example, a simple screw located in a narrow, deep, and small location, may require a severe effort for tool exerting, positioning, and final removal. *Mating face (P2)* refers to the components relative position with each other, which often affects the disassembly-task complexity. The more two components are merged, the more challenging the disassembly-task could be. *Tools (P3)* and *connections type (P4)* are the next two criteria that have influence on the disassembly work. Depending on connections type, appropriate tools are required. *Quantity and variety of connections (P5)* actively makes a disassembly job demanding (Lambert and Gupta, 2004). Each disassembly-task should be evaluated in terms of

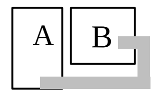
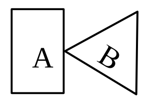
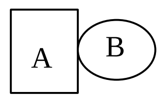
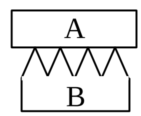
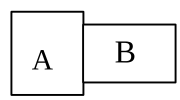
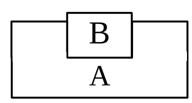
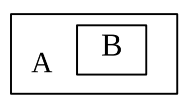
[1] "Delphi is a structured communication technique, originally developed as a systematic, interactive forecasting method which relies on a panel of experts. The experts answer questionnaires in two or more rounds. After each round, a facilitator provides an anonymous summary of the experts' forecasts from the previous round as well as the reasons they provided for their judgments. Thus, experts are encouraged to revise their earlier answers in light of the replies of other members of their panel. Generally, the range of answers decreases and the group converges towards the ''correct'' answer. The process is stopped after a pre-defined stop criterion (e.g. number of rounds, achievement of consensus, and stability of results) and the mean scores of the final rounds determine the results"

these five parameters. In this study, qualitative measures were associated with numerical scales and defined for each parameter (Table 3-2).

Table 3-1 Disassemblability parameters based on state-of-the-art

Authors	Accessibility	Mating face	Tools type	Connection type	Connection quantity
Kroll and Hanft (1998)	✓		✓	✓	✓
Mani et al. (2001)	✓		✓	✓	
Desai and Mital (2003)	✓	✓	✓	✓	✓
Tseng et al. (2008)	✓	✓	✓	✓	
Li et al. (2008)	✓	✓	✓	✓	✓
Mascle and Xing (2009)		✓	✓	✓	
Lai and Gershenson (2009)	✓	✓	✓	✓	✓
Yu et al. (2011)		✓		✓	
Yan and Feng (2013)		✓	✓	✓	✓

Table 3-2 Scales for evaluation of different parameters in a disassembly-task

Disassemblability parameter	Qualitative measure	Numerical scale	Explanations
P1: Accessibility	Very low access	(0-2]	Very deep and very narrow access to the connection
	Limited access	(2-4]	Deep and narrow access to the connection
	Difficult to access	(4-6]	Deep access to the connection
	Moderately accessible	(6-8]	Narrow access to the connection
	Highly accessible	(8-10]	Shallow and broad access to the connection
P2: Mating face	Spacing	(0-1]	
	Single point	(1-2]	
	Line	(2-3]	
	Multi point	(3-5]	
	Single face	(5-7]	
	Multi face	(7-9]	
	Included	(9-10]	
P3: Tools type	No tool	(0-2]	Two components can be disassembled using hands
	Normal tool	(2-4]	Two components can be disassembled using normal tools, like screw driver, wrench…
	Small tool	(4-6]	Two components should be disassembled using small tools with precision.
	Special tool	(6-8]	Two components should be disassembled using special tools, like corner drill, or handy pneumatic tools
	Large tool	(8-10]	Two components should be disassembled using large and heavy tools like, big saws
P4: Connection type	Non-destructive connections	(0-2]	Socket joints, Snap connections
		(2-4]	Different types of screws and bolts which have non-destructive processes
	Destructive connections	(4-6]	Aluminum/steel rivets and i-locks
		(6-8]	Titanium rivets and i-locks, Welding, Adhesive connections
		(8-10]	Tight fitting connections
P5: Quantity and variety of connections	Low quantity	(0-1]	Low quantity of connections with same type
	Medium quantity	(1-2]	Medium quantity of connections with same type
	Low and various quantity	(2-4]	Low quantity of connections with different types
	Medium various quantity	(4-6]	Medium quantity of connections with different types
	High quantity	(6-8]	High quantity of connections with same type
	High and various quantity	(8-10]	High quantity of connections with different types

3.4 Preliminaries and methodology

3.4.1 Relative importance

Although decision-makers agreed on the five pre-mentioned parameters, they may have different opinions on relative importance of each parameter. Relative importance weight indicates how many times one disassemblability parameter is dominant over the other one in decision-maker's point of view. In general, there are two ways to assign relative weights: direct assignment, and eigenvector (Sen and Yang, 1998). In this study, eigenvector was employed to assign the relative weights to the parameters since it is a more reliable and logic method (Saaty, 2008).

Decision-makers evaluated the parameters using pairwise comparison; so if n is the number of parameters, there would be $\frac{n(n-1)}{2}$ comparisons to be performed. Nine-point scale for intensity of dominance between each two parameters was used (Table 3-3); where, "1" indicates no specific dominance between the two parameters and "9" means the overwhelming dominance of a parameter over the other one. Based on the scores obtained, a reciprocal comparison-matrix corresponding to each decision-maker was constructed. After all, eigenvectors for the comparison-matrices were calculated.

Table 3-3 Nine-point scale for intensity of dominance

Definition	Intensity of dominance	Reciprocal intensity
Equally important	1	1
Slightly more important	2	1/2
Weakly more important	3	1/3
Weakly to moderately more important	4	1/4
Moderately more important	5	1/5
Moderately to strongly more important	6	1/6
Strongly more important	7	1/7
Greatly more important	8	1/8
Absolutely more important	9	1/9

Five decision-makers (DM) whom were directly involved in the disassembly job, were asked independently to fill up the questionnaire designed in APPENDIX 3A. Having the data collected, using eigenvector, relative weights were assigned (Table 3-4).

The reliability of the answers given by the decision-makers, was evaluated by calculating the consistency ratio (*CR*) of the obtained comparison-matrices (Table 3-4). According to Saaty (1980), $0 \leq CR < 0.1$ indicates the comparison-matrix is consistent enough. On the contrary, if $CR \geq 0.1$, which is the case for DM2, then the answers might not be reliable and should be sent back to the corresponding decision-maker for possible revision and improve the subjective judgments.

Table 3-4 Different weight-sets using normalized eigenvector

Decision-maker	Disassemblability parameters					*CR*
	P1	P2	P3	P4	P5	
DM1	0.4206	0.0488	0.1644	0.0872	0.2790	0.053
DM2	0.3542	0.0355	0.1588	0.1328	0.3187	0.103
DM3	0.4988	0.2501	0.1115	0.0867	0.0529	0.094
DM4	0.3129	0.0340	0.1596	0.1298	0.3637	0.063
DM5	0.3652	0.1368	0.0726	0.1234	0.3020	0.032

3.4.2 TOPSIS

TOPSIS is a multi-criteria decision-making (MCDM) technique to rank preference based on similarity to ideal solution. In TOPSIS, selected alternatives not only have the shortest distance from the positive ideal solution (PIS), but also the longest distance from the negative ideal solution (NIS) (Hwang and Yoon, 1995). In this study, TOPSIS has been selected among other popular decision-making techniques due to its advantages. In Table 3-5, the advantages of TOPSIS over other MCDM techniques are highlighted based on computation time, simplicity, mathematical calculations, and stability. Numerous studies can be found in the literature that have successfully employed TOPSIS (Behzadian et al., 2012; Mardani et al., 2015; Rostamzadeh et al., 2015; Sánchez-Lozano et al., 2015; Socorro García-Cascales et al., 2012; Ullah et al., 2013; Wang and Chang, 2007; Yue, 2011).

Table 3-5 Comparative performance of some popular MCDM techniques (Wang et al., 2013)

MADM technique	Computation time	Simplicity	Mathematical calculations	Stability
TOPSIS	Moderate	Moderately critical	Moderate	Medium
AHP	Very high	Very critical	Very high	Poor
ELECTREE	High	Moderately critical	Moderate	Medium
PROMETHEE	High	Moderately critical	Moderate	Medium

Assuming that disassembly of the product consists of *m* number of disassembly-tasks, and considering disassembly as a ranking problem, let $D=(d_{ij})_{m\times n}$ (Eq. (3-1)) the decision-matrix where, A_i ($i=1,2,\ldots,m$) are the alternatives (disassembly-tasks) and P_j ($j=1,2,\ldots,n$) are the disassemblability parameters. Consequently, d_{ij} is the input value of the parameter P_j for the alternative A_i.

$$D = \begin{array}{c} \\ A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} P_1 & \cdots & P_j & \cdots & P_n \end{array} \\ \begin{bmatrix} d_{11} & \cdots & d_{1j} & \cdots & d_{1n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{i1} & \cdots & \boldsymbol{d_{ij}} & \cdots & d_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{m1} & \cdots & d_{mj} & \cdots & d_{mn} \end{bmatrix} \end{array} \tag{3-1}$$

Thus, the procedure pursued to implement TOPSIS in this study, is given as follows:

Step 1: Normalization of the decision-matrix (D) via Eq. (3-2). Where, r_{ij} is the normalized value of d_{ij}. The normalized matrix D is named matrix $R=(r_{ij})_{m\times n}$.

$$r_{ij} = \frac{d_{ij}}{\sqrt{\sum_{k=1}^{n} {d_{kj}}^2}};\ i = 1,2,\ldots,m;\ j = 1,2,\ldots,n \tag{3-2}$$

Step 2: Construction of the weighted-normalized decision-matrix $V=(v_{ij})_{m\times n}$ using Eq. (3-3). Where, w_j is the relative importance weight (Table 3-4) allocated to parameter P_j.

$$v_{ij} = w_j . r_{ij}\ ;\ \ i = 1, 2, \dots, m;\ j = 1, 2, \dots, n \tag{3-3}$$

Step 3: Identification of the positive and negative ideal solutions (PIS and NIS) according to Eq. (3-4).

$$PIS = \{v_1^+,\ v_2^+, \dots,\ v_j^+, \dots, v_n^+\};\ \ NIS = \{v_1^-,\ v_2^-, \dots,\ v_j^-, \dots, v_n^-\} \tag{3-4}$$

Where,

$$v_j^+ = \begin{cases} max\ (v_{1j},\ v_{2j},\ \dots,\ v_{mj}) & ;\ P_j \text{ is a } \textbf{benefit} \text{ criterion} \\ min\ (v_{1j},\ v_{2j},\ \dots,\ v_{mj}) & ;\ P_j \text{ is a } \textbf{cost} \text{ criterion} \end{cases}$$

$$v_j^- = \begin{cases} min\ (v_{1j},\ v_{2j},\ \dots,\ v_{mj}) & ;\ P_j \text{ is a } \textbf{benefit} \text{ criterion} \\ max\ (v_{1j},\ v_{2j},\ \dots,\ v_{mj}) & ;\ P_j \text{ is a } \textbf{cost} \text{ criterion} \end{cases}$$

Benefit and ***cost*** criteria are those parameters that positively and negatively influence the disassembly-task, respectively. Among the five parameters taken into account in this study, *accessibility (P1)* was considered as benefit criterion; on the contrary, *mating face (P2)*, *tools type(P3)*, *connections type (P4)*, and *Quantity and variety of connections (P5)* were treated as cost criteria.

Step 4: Calculation of d_i^+ and d_i^- as the Euclidean distances of alternative A_i to PIS and NIS, respectively (Eq. (3-5)).

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_i^+\right)^2}\ ;\ d_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_i^-\right)^2}\ ;\ i = 1, 2, \dots, m \tag{3-5}$$

Step 5: Determination of RC_i as the relative closeness of alternative A_i to the ideal solution (Eq. (3-6)).

$$RC_i = \frac{d_i^-}{d_i^+ + d_i^-}\ ;\ i = 1, 2, \dots, m \tag{3-6}$$

RC_i is a value between 0 and 1; and in this study, it refers to the disassemblability index of the disassembly-task A_i. The higher is RC_i, the easier will be the corresponding disassembly-task. The method is described more in detail in APPENDIX 3B.

3.4.3 Hybrid DOE-TOPSIS method

In previous section we learned how to calculate the disassemblability index for a set of disassembly-tasks using TOPSIS. In MCDM methods, the inputs of decision-matrix (Eq. (3-1)) are required prior to solve the problem, and once an alternative is removed or added, the whole process for MCDM should be redone, which depending on the situation can be laborious and time-consuming (Sabaghi et al., 2015c). Particularly, in disassembly of an aircraft for which a huge amount of disassembly-tasks are required, the application of traditional TOPSIS is questionable. A minor change in the decision-matrix obliges the repetition of the process, which may not be easy to handle. Consequently, count with a dynamic model is more preferred especially in the design phase where modifications and amendments are more common.

Design of experiment (DOE) is well known as an effective statistical method to design and analyze multi-variable processes. DOE helps researchers to determine which subset of variables has the largest influence on the performance of a process (Antony and Capon, 1998; Hambli et al., 2003). In our case, by applying DOE using analysis of variance (ANOVA), the effects of the parameters and their interactions on output from TOPSIS were analyzed. ANOVA is especially suitable in factorial design experiments where different independent sources of variations may be presented (Montgomery, 2013). The sources of variation in this work come from the assessments collected from different decision-makers.

Therefore, integrating DOE and TOPSIS leads to a regression model that allows a facilitated, dynamic, and independent disassembly-task evaluation process. Eq. (3-7) is the mathematical model for DOE-TOPSIS, in matrix view, which links n number of parameters with m number of disassembly-tasks.

$$Y = X\beta + \varepsilon$$

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_i \\ \vdots \\ Y_m \end{bmatrix} = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1n} \\ 1 & x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{i1} & x_{i2} & \cdots & \boldsymbol{x_{ij}} & \ddots & x_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{m1} & x_{m2} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \times \begin{bmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_j \\ \vdots \\ \beta_n \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_i \\ \vdots \\ \varepsilon_m \end{bmatrix} \tag{3-7}$$

Where, Y is the response-vector of RC_i ($i = 1, \dots, m$) values from TOPSIS; X is the coded decision-matrix and consequently x_{ij} is the coded value of d_{ij} in Eq. (3-1); β is the coefficient-vector in which β_0 is the Y-Intercept coefficient and $\beta_j (j = 1, \dots, n)$ are the effects coefficient; and ε is the error-vector including $\varepsilon_i (i = 1, \dots, m)$ errors for the experiments.

3.5 Application process of DOE-TOPSIS

3.5.1 Construction of factorial design for DOE-TOPSIS model

In current study, a two-level full-factorial design (2^5 combinations) was used (Table 3-6). Full-factorial design is an efficient and reliable method due to its ability to measure the effects of all the possible combinations for parameters (Montgomery, 2008). The 32 combinations were considered as the decision-matrix (Eq. (3-1)) in TOPSIS method. Coded values -1 and +1 were used respectively as for the minimum and maximum input values.

Three weight-sets DM1, DM4, and DM5 were employed, due to reasonably low *CR*s associated to them (Table 3-4). Consequently, TOPSIS was performed for every weight-set (as in Section 3.3.2); and the results are tabulated in Table 3-6.

Table 3-6 Factorial design layout for DOE-TOPSIS model (2^5×3 observations)

Std. order	Treatment combination	ABCDE factorial effect	Factor levels					Experimental results via TOPSIS		
			A: P1	B: P2	C: P3	D: P4	E: P5	DM1	DM4	DM5
1	abcde	-	-1	-1	-1	-1	-1	0.446215	0.572617	0.497200
2	bcde	+	+1	-1	-1	-1	-1	1.000000	1.000000	1.000000
3	acde	+	-1	+1	-1	-1	-1	0.441978	0.570372	0.461501
4	cde	-	+1	+1	-1	-1	-1	0.916828	0.938851	0.783493
5	abde	+	-1	-1	+1	-1	-1	0.396227	0.524637	0.487201
6	bde	-	+1	-1	+1	-1	-1	0.757851	0.757367	0.875053
7	ade	-	-1	+1	+1	-1	-1	0.391559	0.522511	0.451279
8	de	+	+1	+1	+1	-1	-1	0.749170	0.752832	0.759729
9	abce	+	-1	-1	-1	+1	-1	0.432596	0.540600	0.468209
10	bce	-	+1	-1	-1	+1	-1	0.859414	0.796094	0.801594
11	ace	-	-1	+1	-1	+1	-1	0.428272	0.538448	0.431608
12	ce	+	+1	+1	-1	+1	-1	0.841575	0.790281	0.722397
13	abe	-	-1	-1	+1	+1	-1	0.381121	0.493793	0.458053
14	be	+	+1	-1	+1	+1	-1	0.731532	0.700423	0.775033
15	ae	+	-1	+1	+1	+1	-1	0.376258	0.491680	0.420946
16	e	-	+1	+1	+1	+1	-1	0.724022	0.697059	0.705288
17	abcd	+	-1	-1	-1	-1	+1	0.275978	0.302941	0.294712
18	bcd	-	+1	-1	-1	-1	+1	0.623742	0.508320	0.579054
19	acd	-	-1	+1	-1	-1	+1	0.268468	0.299577	0.224967
20	cd	+	+1	+1	-1	-1	+1	0.618879	0.506207	0.541947
21	abd	-	-1	-1	+1	-1	+1	0.158425	0.209719	0.277603
22	bd	+	+1	-1	+1	-1	+1	0.571728	0.461552	0.568392
23	ad	+	-1	+1	+1	-1	+1	0.140586	0.203906	0.198406
24	d	-	+1	+1	+1	-1	+1	0.567404	0.459400	0.531791
25	abc	-	-1	-1	-1	+1	+1	0.250830	0.247168	0.240271

Table 3-6 Factorial design layout for DOE-TOPSIS model (25×3 observations) (continue)

26	bc	+	+1	-1	-1	+1	+1	0.608441	0.477489	0.548721
27	ac	+	-1	+1	-1	+1	+1	0.242149	0.242633	0.124947
28	c	-	+1	+1	-1	+1	+1	0.603773	0.475363	0.512799
29	ab	+	-1	-1	+1	+1	+1	0.083172	0.061149	0.216507
30	b	-	+1	-1	+1	+1	+1	0.558022	0.429628	0.538499
31	a	-	-1	+1	+1	+1	+1	0.000000	0.000000	0.000000
32	(1)	+	+1	+1	+1	+1	+1	0.553785	0.427383	0.502800

3.5.2 Analysis of variance (ANOVA)

To do the ANOVA, *Minitab*® software package version 17.1 was utilized with five-factor interaction (5-FI). A half-normal probability plot with 95% confidence interval (β=95% and α=5%) was used to find the significant factors and their interactions (Figure 3-1). The reference line, in Figure 3-1, indicates where the points were expected to fall if the effects for the corresponding terms were zero. Significant effects are shown in square points and labeled in the figure. This means that the *p*-values for these points were less than or equal to 0.05 (α=5%). *P*-value is the probability when the *null hypothesis* (the effect is not significant) is true. Therefore, points with *p*-values>0.05 were concluded as non-significant. The estimated effects, coefficients, and standard errors (SE) for parameters and their interactions are summarized in Table 3-7[2]; the rows in bold indicate that the terms are significant.

[2] *t*-value is associated with *p*-value test to find out the significant parameters in the model. *t*-value is the distribution of differences and in our model, when |*t*-value|≥2, it indicates that the corresponding parameter is significant.

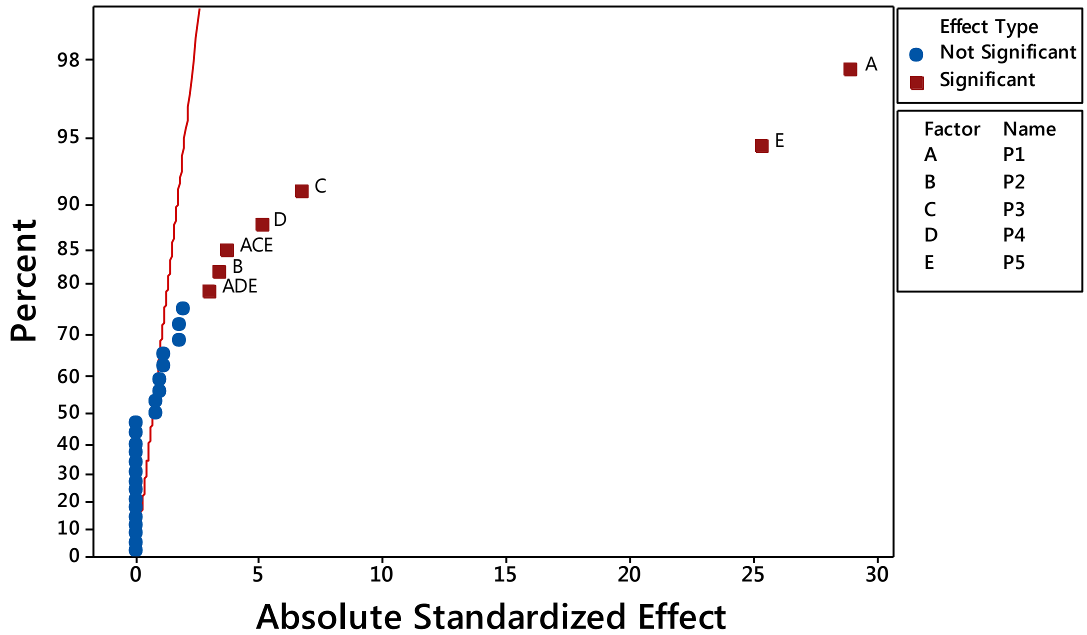


Figure 3-1 Half-normal probability plot for five-factor interaction (α=5%)

Table 3-7 Estimated effects of parameters and their interactions

Term	Effect	Coded Coefficient	SE Coefficient	*t*-value	*p*-value
Constant		**0,50000**	**0,00572**	**87,41**	**0,000**
P1	**0,33125**	**0,16563**	**0,00572**	**28,95**	**0,000**
P2	**-0,03827**	**-0,01914**	**0,00572**	**-3,35**	**0,001**
P3	**-0,07656**	**-0,03828**	**0,00572**	**-6,69**	**0,000**
P4	**-0,05808**	**-0,02904**	**0,00572**	**-5,08**	**0,000**
P5	**-0,29022**	**-0,14511**	**0,00572**	**-25,37**	**0,000**
P1*P2	-0,00000	-0,00000	0,00572	-0,00	1,000
P1*P3	-0,00000	-0,00000	0,00572	-0,00	1,000
P1*P4	0,00000	0,00000	0,00572	0,00	1,000
P1*P5	0,00000	0,00000	0,00572	0,00	1,000
P2*P3	-0,00000	-0,00000	0,00572	-0,00	1,000
P2*P4	-0,00000	-0,00000	0,00572	-0,00	1,000
P2*P5	-0,00000	-0,00000	0,00572	-0,00	1,000
P3*P4	-0,00000	-0,00000	0,00572	-0,00	1,000
P3*P5	-0,00000	-0,00000	0,00572	-0,00	1,000
P4*P5	-0,00000	-0,00000	0,00572	-0,00	1,000
P1*P2*P3	0,01101	0,00550	0,00572	0,96	0,340

Table 3-7 Estimated effects of parameters and their interactions (continue)

P1*P2*P4	0,01318	0,00659	0,00572	1,15	0,253
P1*P2*P5	0,02236	0,01118	0,00572	1,95	0,055
P1*P3*P4	0,02044	0,01022	0,00572	1,79	0,079
P1*P3*P5	**0,04218**	**0,02109**	**0,00572**	**3,69**	**0,000**
P1*P4*P5	**0,03426**	**0,01713**	**0,00572**	**2,99**	**0,004**
P2*P3*P4	0,00892	0,00446	0,00572	0,78	0,439
P2*P3*P5	0,01091	0,00545	0,00572	0,95	0,344
P2*P4*P5	0,01305	0,00652	0,00572	1,14	0,258
P3*P4*P5	0,02044	0,01022	0,00572	1,79	0,079
P1*P2*P3*P4	-0,00000	-0,00000	0,00572	-0,00	1,000
P1*P2*P3*P5	-0,00000	-0,00000	0,00572	-0,00	1,000
P1*P2*P4*P5	0,00000	0,00000	0,00572	0,00	1,000
P1*P3*P4*P5	-0,00000	-0,00000	0,00572	-0,00	1,000
P2*P3*P4*P5	-0,00000	-0,00000	0,00572	-0,00	1,000
P1*P2*P3*P4*P5	0,00888	0,00444	0,00572	0,78	0,441

3.5.3 Regression model

Based on the estimated coefficients (Table 3-7) a fitted regression model for the disassembly problem was built (Eq. (3-8)). $\hat{Y}$ is the predicted disassemblability index ($0 \leq \hat{Y} \leq 1$); and $X_1, X_2, \ldots, X_5$ are the coded input values for the parameters *P1*, *P2*,…, *P5*, respectively.

$$\begin{aligned}\hat{Y} = 0.5 + 0.16563X_1 - 0.01914X_2 - 0.03828X_3 - 0.02904X_4 - 0.14511X_5 \\ + 0.02109X_1X_3X_5 + 0.01713X_1X_4X_5\end{aligned} \tag{3-8}$$

Subjected to: $-1 \leq X_1, X_2, X_3, X_4, X_5 \leq 1$

Eq. (3-9) gives the relationship between coded and un-coded parameters inputs.

$$X_j = \frac{\mathrm{p}_j - \left(\mathrm{p}_j(max) + \mathrm{p}_j(min)\right)/2}{\left(\mathrm{p}_j(max) - \mathrm{p}_j(min)\right)/2} \; ; \; j = 1, 2, \ldots, 5 \tag{3-9}$$

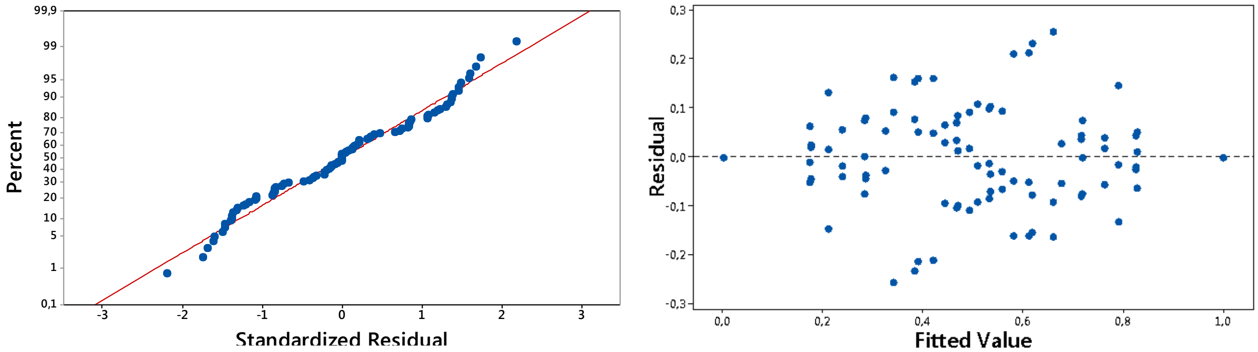
Where, p_j $(j = 1,2, \dots ,5)$ are the un-coded input values for the corresponding parameter *P1, P2,…, P5*; and $\mathrm{p}_j(min) \leq \mathrm{p}_j \leq \mathrm{p}_j(max)$.

R^2 and $R^2(adj)$, in Table 3-8, represent how close the real data to the fitted regression line are. In our case, $R^2(adj)$ explains that the 94.30% of the variations in TOPSIS results can be explained by the variations of independent terms given in the regression model (Eq. (3-8)).

Table 3-8 Summary of ANOVA results for DOE-TOPSIS

Source	DF	Adj. SS	Adj. MS	*F*-value	*p*-value
Main effects	5	4.91168	0.98234	21.59	0.000
2-Way Interactions	10	0.00000	0.00000	3.29	0.000
3-Way Interactions	10	0.11885	0.01188	1.47	0.173
4-Way Interactions	5	0.00000	0.00000	1.54	0.191
5-Way Interactions	1	0.00189	0.00189	1.64	0.205
Error	64	0.20104	0.00314		
Total	95	5.23346			
R^2=96.16% $R^2(adj)$=94.30%					

Figure 3-2.a plotted the normal probability residuals for the regression model. Residual is the difference between observed (Y) and fitted ($\hat{Y}$) values. The figure shows that the residuals approximately fall over the reference line. This means that the regression model is adequate and reasonably fits the data. Thus, there is no need for addition of other coefficients in the current model. Besides, according to Montgomery (2008), the model is satisfactory if the residuals versus fitted values are structureless; which, in our case, Figure 3-2.b reveals no obvious pattern.



(a) (b)

Figure 3-2 Residuals and model adequacy: a) Normal probability plot; b) Residuals versus fitted value plot

3.6 Validation and discussion

To rely on the robustness of the developed model, a validation was performed by comparing the results obtained from the regression model and traditional TOPSIS. To this aim, 20 disassembly-tasks (DT) were considered as the ones required to disassemble a part of the aircraft. As previously discussed, each disassembly-task was evaluated in terms of the five pre-defined parameters. The scores assigned to parameters were randomly generated (Figure 3-3). This allows to eliminate the bias by giving all the alternatives an equal chance to be chosen. Both, regression model and traditional TOPSIS methods were applied to calculate the disassemblability indices. The results for both methods follow a similar pattern, as plotted in Figure 3-3.

Looking at the disassemblability indices, DT17 and DT4 appear as the easiest and most difficult disassembly-tasks for both methods, respectively. The disassembly-tasks can be categorized in terms of the corresponding indices. We assumed that, indices from 0 to 0.3 as “difficult to disassemble”; between 0.3 and 0.7 as “mild to disassemble”; and the range between 0.7 and 1 as “easy to disassemble”. This information can be useful, specifically at the design phase, to make modifications in order to improve the current design to be more appropriate for disassembly at the end-of-life. It is worth to mention that, the modifications into the design should be done wisely. It can happen that an improvement into one disassembly-task results in worsening of the other(s) due to the fact that components are often physically interacting with each other.

Thinking about design for modularity, having these results, allows designers to create modules that aggregate the most convenient components depending on the final destination of the module at the end-of-life. For example a module destined for recycling should be easy to disassemble as a whole piece; meanwhile the components inside can be difficult to disassemble but ideally composed of the same material. The same approach can be applied for different design purposes as for maintenance, assembly, reuse, remanufacture, etc.

In terms of disassembly sequencing, removing one component might improve the "*accessibility*" and "*mating face*" for the next remaining components to be disassembled. As a result, the application of traditional TOPSIS, although it can provide good results, every time one component is removed the input parameters for all the remaining components should be revised in the decision-matrix; which can be tedious, laborious and time consuming. On the other hand, by using DOE-TOPSIS and consequently establishing the regression model, there is no need to construct a decision-matrix each time we need to evaluate the indices. The model can be simply used to evaluate each disassembly-task individually based on the "disassembly state". As a result, the model proposed can be used as an objective function in order to select the optimum disassembly sequence for the product.

	DT1	DT2	DT3	DT4	DT5	DT6	DT7	DT8	DT9	DT10	DT11	DT12	DT13	DT14	DT15	DT16	DT17	DT18	DT19	DT20
P1	6.8	8.9	7.0	0.5	3.8	8.7	4.9	6.8	2.2	7.9	9.7	5.0	7.8	7.2	9.3	6.8	8.6	3.1	5.8	9.2
P2	2.4	9.5	0.5	8.4	1.6	3.0	7.1	3.1	6.4	1.4	2.4	3.7	5.5	2.2	5.2	7.9	3.0	6.5	4.8	0.2
P3	3.4	6.1	6.3	9.3	8.1	3.5	0.1	8.7	9.7	8.2	3.5	4.8	4.2	0.4	2.7	5.1	2.4	8.9	9.8	3.7
P4	9.4	2.6	6.9	7.8	0.2	9.2	7.5	7.6	5.8	9.9	2.6	5.5	0.6	7.8	3.0	7.2	0.9	8.0	5.1	10.0
P5	7.2	7.8	1.8	9.8	0.5	0.3	1.9	6.3	3.6	6.2	9.4	7.1	0.1	9.9	6.0	8.5	0.1	2.9	7.9	1.3

Figure 3-3 Randomly generated inputs (un-coded) for parameters; and results

3.7 Conclusion and further studies

An aircraft should be designed in a way that at the time of retirement is considered as a source of valuable materials easy to process. Therefore, engineers have to take actions to find innovative solutions and methodologies at the design phase that facilitate the products' end-of-life treatment. Disassembly has a deterministic role in increasing the value-added of the products not only at end-of-life stage, but during the life time and maintenance as well. In this study, disassembly was considered as a decision-making problem and application of TOPSIS was proposed accordingly. Even though, the idea of employing TOPSIS in disassembly problems *per se* is genuine, it carries some limitations. Indeed, using traditional TOPSIS, the disassemblability indices for the disassembly-tasks cannot be obtained independently. Thus, a hybrid DOE-TOPSIS method was introduced to develop a regression model for disassembly of a Bombardier Regional Jet aircraft. A two-level full-factorial DOE was used to generate the appropriate decision-matrix and evaluate the effects of the parameters and their interactions on the TOPSIS results.

First, the significant disassembly parameters and the interactions between them were pinned point. The results showed that among the analyzed disassembly parameters in the main structure of the aircraft, "*Accessibility*" and "*Quantity and variety of the connections*" are the most significant ones which can highly influence the disassembly-task. This result gives the idea to designers about the most important parameters they should respect during the design of the product. Then, a polynomial regression model was developed for estimating the disassemblability index. The results from ANOVA showed a 94.30% of reliability, and testified the adequacy of the model. The model was validated using 20 randomly generated inputs for the parameters, showing a very similar pattern to the one obtained from traditional TOPSIS.

The proposed model can be used by decision-makers, and designers for reengineering purposes. They can easily and practically evaluate the disassemblability indices among the different components to improve the disassembly and in a broader scope recoverability of the future products at the end-of-life. Also our hybrid methodology is applicable for other industries such as automotive, naval, railway and so on; since they also have challenges regarding their products' design, assembly, disassembly, maintenance, and end-of-life. Accordingly, they need to identify the appropriate parameters, but the methodology remains the same.

To overcome the uncertainty and fuzziness potentially derived from MCDM problems, application of fuzzy MCDM methods such as fuzzy-TOPSIS can be useful to perform a more accurate evaluation. The proposed model will be employed in "design for modularity" for components clustering in order to define modules with high disassemblability while preserving the functionality and suitable sustainability.

3.8 ACKNOWLEDGEMENTS

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3.9 APPENDIX 3A

Sample questionnaire obtained from DM4:

	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Accessibility	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	Mating face
Accessibility	○	○	○	○	○	○	●	○	○	○	○	○	○	○	○	○	○	Tool type
Accessibility	○	○	○	○	○	○	○	●	○	○	○	○	○	○	○	○	○	Connection type
Accessibility	○	○	○	○	○	○	○	○	●	○	○	○	○	○	○	○	○	Quantity and variety of connections
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Mating face	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	Tool type
Mating face	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	Connection type
Mating face	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	Quantity and variety of connections
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Tool type	○	○	○	○	○	○	○	●	○	○	○	○	○	○	○	○	○	Connection type
Tool type	○	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○	○	Quantity and variety of connections
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Connection type	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	○	○	Quantity and variety of connections

3.10 APPENDIX 3B

The calculated disassemblability indices (RC_i) are based on the **relative closeness** of the alternatives to the ideal solution. This means that the selected alternative not only has the closest distance to the positive ideal solution (PIS) but the farthest distance to the negative ideal solution (NIS). To make this explanation clearer, assuming we have two parameters (X_1 and X_2) with positive characteristics (the higher the better) as shown in the Appendix 3B-Figure 3-4.

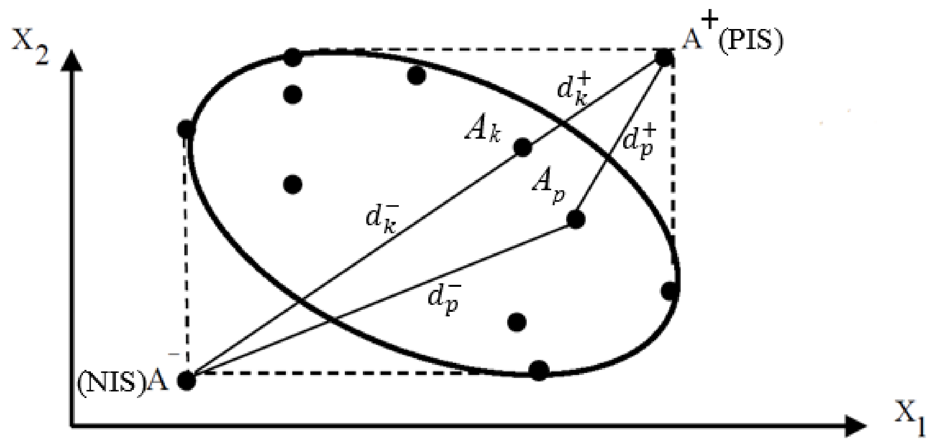
A^+ and A^- are the PIS and NIS, respectively; and in between, we have all the alternatives. Considering two alternatives A_k and A_p; where, A_k has the closer distance to A^+ while A_p has the farther distance to A^-. d_k^+ and d_p^+ are the distances of the alternatives to PIS. And, d_k^- and d_p^- are the distances of the alternatives to NIS. Therefore, using relative closeness the priorities of alternatives A_1 and A_2 are calculated as $RC_k = \frac{d_k^-}{d_k^- + d_k^+}$ and $RC_p = \frac{d_p^-}{d_p^- + d_p^+}$. The one has the higher value of relative closeness, is determined as the better one.

This may raise the question that: Can an inconsistency occur for "disassembly indices" while applying TOPSIS? In other words, can A_k be better than alternative A_p (which means $RC_k > RC_p$) if A_k has a greater distance to PIS in compare to A_p , but at the same time A_k is also significantly far from NIS in compare compared to A_p?

To make it clear, the problem has been formulized as follows:

1) if A_k is significantly far from NIS, $d_k^- \to \infty$ which means: $d_k^+ \to 0$ and consequently the relative closeness to A^+ will be: $\lim_{d_k^- \to \infty} \frac{d_k^-}{d_k^- + d_k^+} = \frac{1}{1} = 1$.
2) if A_p is significantly close to PIS, $d_p^+ \to 0$ which means: $d_p^- \to \infty$ and consequently the relative closeness to A^+ will be: $\lim_{d_p^+ \to 0} \frac{d_p^-}{d_p^- + d_p^+} = \frac{d_p^-}{d_p^-} = 1$.

So as can be seen, in such a situation the both A_k and A_p will be concluded actually as one solution, where $A_k = A_p = A^+$ with relative closeness equal to 1.



Appendix 3B-Figure 3-4 Illustration of TOPSIS with two attributes having positive characteristics

3.11 REFERENCES

Airbus, S.A.S., 2008. Process for advanced management of end-of-life of aircraft (PAMELA), France.

Åkermark, A.-M., 1997. *Design for disassembly and recycling, Life cycle networks*. Springer, pp. 237-248.

Antony, J., Capon, N., 1998. Teaching experimental design techniques to industrial engineers. *International journal of engineering education 14,* 335-343.

Asmatulu, E., Overcash, M., Twomey, J., 2013a. Recycling of aircraft: State of the art in 2011. *Journal of Industrial Engineering*, 1-8.

Asmatulu, E., Twomey, J., Overcash, M., 2013b. Evaluation of recycling efforts of aircraft companies in Wichita. *Resources, Conservation and Recycling 80*, 36-45.

Behzadian, M., Khanmohammadi Otaghsara, S., Yazdani, M., Ignatius, J., 2012. A state-of the-art survey of TOPSIS applications. *Expert Systems with Applications 39,* 13051-13069.

Blume, T., Walther, M., 2013. The end-of-life vehicle ordinance in the German automotive industry – corporate sense making illustrated. *Journal of Cleaner Production 56*, 29-38.

Collado-Ruiz, D., Capuz-Rizo, S.F., 2010. Modularity and ease of disassembly: Study of electrical and electronic equipment. *Journal of Mechanical Design 132*, 1, 14502-14504.

CRIAQ-ENV412, Process for advanced management and technologies of aircraft end-of-life, http://www.polymtl.ca/env412/index.php,

Das, S.K., Kaufman, J.G., 2008. Recycling aluminum aerospace alloys. *Light Metals, TMS*, 1161-1165.

Das, S.K., Yedlarajiah, P., Narendra, R., 2000. An approach for estimating the end-of-life product disassembly effort and cost. *International Journal of Production Research 38*, 657-673.

Desai, A., Mital, A., 2003. Evaluation of disassemblability to enable design for disassembly in mass production. *International Journal of Industrial Ergonomics 32*, 265-281.

Duflou, J.R., Seliger, G., Kara, S., Umeda, Y., Ometto, A., Willems, B., 2008. Efficiency and feasibility of product disassembly: A case-based study. *CIRP Annals - Manufacturing Technology 57*, 583-600.

Feldhusen, J., Pollmanns, J., Heller, J.E., 2011. *End of life strategies in the aviation industry*, Glocalized Solutions for Sustainability in Manufacturing. Springer, Technische Universität Braunschweig, Braunschweig, Germany, 459-464.

Giudice, F., 2010. Disassembly depth distribution for ease of service: a rule-based approach. *Journal of Engineering design 21*, 375-411.

Giudice, F., Kassem, M., 2009. End-of-life impact reduction through analysis and redistribution of disassembly depth: A case study in electronic device redesign. *Computers & Industrial Engineering 57*, 677-690.

Hambli, R., Richir, S., Crubleau, P., Taravel, B., 2003. Prediction of optimum clearance in sheet metal blanking processes. *The International Journal of Advanced Manufacturing Technology 22*, 20-25.

Huang, C.-C., Liang, W.-Y., Chuang, H.-F., Chang, Z.-Y., 2012. A novel approach to product modularity and product disassembly with the consideration of 3R-abilities. *Computers & Industrial Engineering 62*, 96-107.

Hwang, C.-L., Yoon, K., 1995. *Multiple attribute decision making: An introduction*. Springer.

Kroll, E., Hanft, T.A., 1998. Quantitative evaluation of product disassembly for recycling. *Research in Engineering Design 10*, 1-14.

Lai, X., Gershenson, J.K., 2009. *DSM-based product representation for retirement process-based modularity*, ASME/IEEE international conference on mechatronic and embedded systems and applications. ASME, Beijing, China, pp. 791-805.

Lambert, A., 1997. Optimal disassembly of complex products. *International Journal of Production Research 35*, 2509-2524.

Lambert, A.F., Gupta, S.M., 2004. *Disassembly modeling for assembly, maintenance, reuse and recycling*. Boca Raton: CRC press.

Latremouille-Viau, J., Baptiste, P., Mascle, C., 2010. *Airframe dismantling optimization for aerospace aluminum valorization*, In: Lee, S., Suárez, R., Choi, B.-W. (Eds), Frontiers of Assembly and Manufacturing. Springer Berlin Heidelberg, 157-169.

Li, J., Zhang, H.-C., Gonzalez, M.A., Yu, S., 2008. A multi-objective fuzzy graph approach for modular formulation considering end-of-life issues. *International Journal of Production Research 46*, 4011-4033.

Mani, V., Das, S., Caudill, R., 2001. *Disassembly complexity and recyclability analysis of new designs from CAD file data*, IEEE International Symposium on Electronics and the Environment. IEEE, Denver, Colorado, 10-15.

Mardani, A., Jusoh, A., Zavadskas, E.K., 2015. Fuzzy multiple criteria decision-making techniques and applications – Two decades review from 1994 to 2014. *Expert Systems with Applications 42*, 4126-4148.

Mascle, C., 2013. Design for rebirth (DFRb) and data structure. *International Journal of Production Economics 142*, 235-246.

Mascle, C., Baptiste, P., Sainte-Beuve, D., Camelot, A., 2015. Process for advanced management and technologies of aircraft EOL. *Procedia CIRP 26*, 299-304.

Mascle, C., Xing, K., 2009. A liaison model for disassembly-reassembly product ecodesign. *International Journal of Design Engineering 2*, 346-368.

McCluskey, F.P., Sandborn, P., Gupta, S.K., Magrab, E.B., 2009. *Design for assembly and disassembly*. In: Integrated product and process design and development: the product realization process, 2ed ed. CRC Press, 145-154.

Millet, D., Yvars, P.-A., Tonnelier, P., 2012. A method for identifying the worst recycling case: Application on a range of vehicles in the automotive sector. *Resources, Conservation and Recycling 68*, 1-13.

Montgomery, D.C., 2008. *Design and analysis of experiments*. John Wiley & Sons.

Montgomery, D.C., 2013. Applied Statistics and Probability for Engineers 6th edition. Wiley.

Qian, X., Zhang, H.C., 2009. Design for environment: An environmentally conscious analysis model for modular design. *IEEE Transactions on Electronics Packaging Manufacturing 32*, 164-175.

Rose, C.M., Stevels, A., Ishii, K., 2000. A new approach to end-of-life design advisor (ELDA). *IEEE International Symposium on Electronics and the Environment*, 99-104.

Rostamzadeh, R., Sabaghi, M., Sofian, S., Ismail, Z., 2015. Hybrid GA for material routing optimization in supply chain. *Applied Soft Computing 26*, 107-122.

Saaty, T., 1980. *The analytic hierarchy process*. McGraw-Hill, New York.

Saaty, T.L., 2008. Decision making with the analytic hierarchy process. *International Journal of Services Sciences 1*, 83-98.

Sabaghi, M., Cai, Y., Mascle, C., Baptiste, P., 2015a. Sustainability assessment of dismantling strategies for end-of-life aircraft recycling. *Resources, Conservation and Recycling 102*, 163-169.

Sabaghi, M., Cai, Y., Mascle, C., Baptiste, P., 2015b. Towards a sustainable disassembly/dismantling in aerospace industry. *Procedia CIRP 40*, 156–161.

Sabaghi, M., Mascle, C., Baptiste, P., 2015c. Application of DOE-TOPSIS technique in decision-making problems. *IFAC-PapersOnLine 48*, 773-777.

Sánchez-Lozano, J.M., Serna, J., Dolón-Payán, A., 2015. Evaluating military training aircrafts through the combination of multi-criteria decision making processes with fuzzy logic. A case study in the Spanish Air Force Academy. *Aerospace Science and Technology 42*, 58-65.

Sen, P., Yang, J.-B., 1998. *Multiple criteria decision support in engineering design*. Springer London.

Socorro García-Cascales, M., Teresa Lamata, M., Miguel Sánchez-Lozano, J., 2012. Evaluation of photovoltaic cells in a multi-criteria decision making process. *Annals of Operations Research 199,* 373-391.

Suga, T., Saneshige, K., Fujimoto, J., 1996. *Quantitative disassembly evaluation*. Proceedings of the 1996 IEEE International Symposium on Electronics and the Environment (ISEE-1996), 19-24.

Tseng, H.-E., Chang, C.-C., Li, J.-D., 2008. Modular design to support green life-cycle engineering. *Expert Systems with Applications 34,* 2524-2537.

Ullah, R., Zhou, D.-Q., Zhou, P., Hussain, M., Amjad Sohail, M., 2013. An approach for space launch vehicle conceptual design and multi-attribute evaluation. *Aerospace Science and Technology 25*, 65-74.

Viswanathan, S., Allada, V., 2001. Configuration analysis to support product redesign for end-of-life disassembly. *International Journal of Production Research 39*, 1733-1753.

Wang, P., Meng, P., Zhai, J.-Y., Zhu, Z.-Q., 2013. A hybrid method using experiment design and grey relational analysis for multiple criteria decision making problems. *Knowledge-Based Systems 53*, 100-107.

Wang, T.-C., Chang, T.-H., 2007. Application of TOPSIS in evaluating initial training aircraft under a fuzzy environment. *Expert Systems with Applications 33*, 870-880.

Yan, J., Feng, C., 2013. Sustainable design-oriented product modularity combined with 6R concept: a case study of rotor laboratory bench. *Clean Technologies and Environmental Policy 16*, 95-109.

Yu, S., Yang, Q., Tao, J., Tian, X., Yin, F., 2011. Product modular design incorporating life cycle issues-Group Genetic Algorithm (GGA) based method. *Journal of Cleaner Production 19*, 1016-1032.

Yue, Z., 2011. An extended TOPSIS for determining weights of decision makers with interval numbers. *Knowledge-Based Systems 24*, 146-153.

CHAPTER 4 ARTICLE 2: SUSTAINABILITY ASSESSMENT OF DISMANTLING STRATEGIES FOR END-OF-LIFE AIRCRAFT RECYCLING

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4.1 ABSTRACT

With the current increase of environmental concerns, conventional methods practiced at end-of-life would not be capable to sustain the growing amount of retired aircrafts waiting for final disposal in the scrap yards each year. Material recycling is known as an important environmentally friendly activity. The quality of recycled material in a recycling process is actively influenced by an appropriate disassembly/dismantling strategy. In recycling the carcass of the aircraft, it is suitable to separate and classify different aluminum grades into their main alloys family before sending them to recycling center (i.e. 2xxx and 7xxx). However, due to complexity in the aircraft structure, fully disassembly/dismantling or fully shredding the aircraft is not economically or environmentally viable, respectively. For this reason, this work discusses eight different disassembly/dismantling strategies that have been done on a real Bombardier Regional Jet aircraft. The study narrows the gap in sustainability evaluation of these strategies by using an efficient fuzzy assessment method. Ten different risk scenarios were considered to have a robust understanding about the sustainability performance of each strategy. The methodology used in this work allowed to select the best strategy in terms of sustainable disassembly/dismantling.

Keywords: Sustainability evaluation; Sustainable dismantling; Aircraft end-of-life; Recycling; Fuzzy inference system

4.2 Introduction

According to Airbus's report (Airbus, 2008), "Process for Advanced Management of End-of-Life of Aircraft (PAMELA)", around 85% of the weight of a civil aircraft can be recovered (15% for reuse, and 70% through recycling). Recycling includes collecting and sorting recyclable materials that would otherwise be considered as waste and then processing them into raw materials for future aircrafts or other industrial applications. Excellent environmental benefits come out from recycling high-tech aerospace alloys rather than production from virgin materials (Asmatulu et al., 2013a).

Sustainability and sustainable development are more and more becoming the center of attention for different industries. Ideally, in sustainable development should be considered the entire supply chain including end-of-life (Jayal et al., 2010). Frosch and Gallopoulos (1989) pointed out: "Wastes (end-of-life materials) from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment". Acting as supplier for bigger industries, aircraft dismantler/recycler businesses should focus on strategies that allow to ameliorate their current position in the market. One of the key factors is to practice sustainability and sustainable development in all the dismantling and recycling processes.

One of the major problems in recycling aircrafts is aluminum recycling. An interesting study performed in aircraft manufacturing facilities in Wichita, revealed that only 20% of the potential recyclable aluminum from 1765 aircrafts was actually recycled (Asmatulu et al., 2013b). Shredding has been extensively used as a pre-recycling method that allows transforming huge components of the aircraft into smaller and more practical dimensions. Fully shredding an aircraft as a whole piece, results in a mixture of different aluminum alloys with different grades and leads to a very low alloy quality. This low quality aluminum requires additional treatments to recuperate the mechanical properties that make it suitable for appropriate applications.

Although efforts have been directed towards improving the aluminum recycling methods (Gaustad et al., 2012; Grimes et al., 2008), the lower is the quality of the aluminum alloy retrieved, more additional treatments are required and more costs associated. In this situation, it is preferable to disassemble/dismantle the components with different grades of aluminum alloys into their main alloy families prior to shredding (Das and Kaufman, 2008; Mascle et al., 2015).

In our knowledge, little attention has been paid to implementation of dismantling and pre-sorting strategies that can ameliorate the quality of alloys prior to recycling. In this study, eight different disassembly/dismantling strategies before shredding were developed under the project "*Process for advanced management and technologies of aircraft end-of-life*" (CRIAQ-ENV412). These strategies were applied to a real Bombardier Regional Jet aircraft. The main focus of this paper is to shed the light on process of sustainable strategy selection in different risk scenarios. The three-bottom-line (TBL) concept (environmental, economic, and social sustainability) was taken into account.

Including this introduction, Section 4.3 presents the eight disassembly/dismantling strategies; in Section 4.4, hierarchical structure for the TBL is introduced; the application of a fuzzy assessment is presented in Section 4.5; evaluation of the strategies in different risk scenarios is given in Section 4.6; and finally, Section 4.7 presents the conclusion.

4.3 Disassembly/dismantling strategies

The main goal of testing different disassembly/dismantling strategies is to minimize the cost-benefit ratio and environmental impact of the recycling process. Cost is dependent on the time and number of employees required. Benefit can be translated as the market value of the retrieved material. A homogenous package composed of the same material is more valuable than scraps: mixture of different materials. It is worth mentioning that the relevance of costs and benefits may vary considering the local context (e.g. country, city, urban or rural environment). For instance, the labor cost in China is less than the one in North America. This fact might influence the selection of the final strategy depending on the local context.

Disassembly is the act of separation, and separation is acquired when the joints for the two components are clearly removed (Lambert and Gupta, 2004). A rigorous disassembly can be tedious and time-consuming, but is the best way to avoid cross contamination of different materials for recycling purposes. On the other hand, the action of cutting is to make an opening or incision in (something) with a sharp-edged tool or object. In terms of dismantling operations, cutting has been commonly used. However, cutting parts usually implicates that a certain portion of material *X* will be mixed with a higher concentrated material *Y*.

Strategy A — Systematic disassembly: The purpose of this strategy is to separate and sort all the components based on material composition. The attachments are also removed and sorted. The identification of the material is performed using Niton, portable X-Ray fluorescence analyzer. Typically, the removal of one aluminum rivet takes 15 to 20 seconds; while that of for titanium rivet is more than 2 minutes. Disassembling the top-skin of the Regional Jet left horizontal stabilizer takes an entire work day. Although *Systematic disassembly* is labor intensive, it is the best strategy in terms of segregation of different type of materials. In other words, this strategy is concentrated on quality rather than quantity.

Strategy B — Shredding: The aircraft is cut into small pieces for transportation to recycling center. Each piece is compound of different types of materials: aluminum, titanium, steel, plastics, composite, glasses, rubber, etc. Unlike *Strategy A*, *Shredding* is concentrated on quantity rather than quality.

A and *B* strategies are considered the extremes in cost-benefit ratio. *Strategy A* has the highest potential cost and highest quality of retrieved materials; on the contrary, *Strategy B* has the lowest for both. *A* and *B* are not fully desired to be practiced in industries because of the excessive costs and poor material quality associated to *A* and *B*, respectively. Intermediate strategies can be defined using the available mapping of the aircraft. The mapping contains information for material composition of each component. The following strategies are based on the use of this aircraft mapping.

Strategy C — Smart shredding: Instead to cut the carcass randomly in pieces, *Smart shredding* selects zones on the carcass based on the mapping. The selection takes regions with higher frequency in similar type of materials. This fact may result in more homogeneous pieces before shredding. However a very limited number of cuts are established in this strategy.

Additionally, it is remarkable to mention that when the selected piece is removed a mass balancing analysis is required to estimate the type of alloy that will be retrieved. This information helps stakeholders to save the intrinsic properties of the materials.

Strategy D — Gross cutting: This strategy is conceptually similar to *Strategy C*, but more cuttings are allowed. Consequently, powerful and moveable cutting tools are required. These tools are often bulky and fuel-based permitting to cut fast but noticeably imprecise.

Strategy E — Semi-gross cutting: Unlike *Strategy D* this strategy requires more precise cuts in order to increase the homogeneity of the packages. More precision demands for lighter and powerful cutting tools. Most of these tools are electrical.

Strategy F — Detail cutting: As the name suggests, this strategy implies a high amount of precise cuttings. It obliges to have more precise tools, which are usually smaller and handy pneumatic tools. Unlimited cuts are allowed which implies that this strategy be laborious and time-consuming.

Strategy G — Smart disassembly: The main concern about *Systematic disassembly* is the time and effort spent to remove the attachments. The question is: "Do we really need to remove all the attachment?" The goal of this strategy is to alleviate the excessive time needed to remove the attachments in *Strategy A* by NOT removing rivets that are shared between components with similar material composition. Though, the quality of recovered material is compromised due to inclusion of these attachments.

Strategy H — Disassembly combined with cutting: In this strategy, *Systematic disassembly* and *Detail cutting* are combined. First, a meticulous analysis of the whole carcass or the pieces to be recycled needs to be accomplished. The areas to be cut are the ones with higher density of the same or similar materials; on the contrary disassembly should be done in heterogeneous regions where each component has a different material.

4.4 **Sustainability drivers**

After group meeting with the partners and decision-makers in the project, it was decided to analyze the strategies with respect to TBL concept. This process of knowledge extraction from the experts was performed using pseudo Delphi method. Having presented the problem and importance of sustainability as a key factor, decision-makers agreed that the TBL approach was suitable to solve the problem.

In the following part of the survey, experts were advised that one of the important steps to start the analysis is to determine the appropriate sustainability criteria and indicators. Although there can be found plenty of indicators in the literature, existing criteria might not be fully suitable in our problem case. Therefore, the most important and time consuming part of this study was to select the proper criteria and indicators. The hierarchical structure for TBL, criteria and evaluation indicators for this work are shown in Figure 4-1.

Waste generation (WG)(An et al., 2014; Dursun et al., 2011) quantifies amount of waste produced during the implementation of the strategies. Consumable material (CM) includes all the materials involved to perform appropriate disassembly/dismantling operations. Retrieved material homogeneity (RmH)(Mascle et al., 2015) measures the homogeneity level of the alloys recovered at the end of the strategy implementation. This indicator is conceived as an environmental factor (Kohut, 2003) because as higher the quality of the retrieved material, the lower will be the consumption of natural resources.

Once the carcass is split in packages depending on the strategy that has been implemented, the packages will have different prices based on the homogeneity of the alloys. This fact is reflected into Market price (MP). Subsidiary costs (SC) include costs such as storage, transportation, handling, etc. Energy cost (EC) is the cost of energy consumed during the implementation of the strategies. Operational cost (OC) covers the costs derived from number of workers and salaries, depreciation of equipment, etc. Equipment cost (EqC) includes the expenses related to instruments, tools, safety equipment, etc.

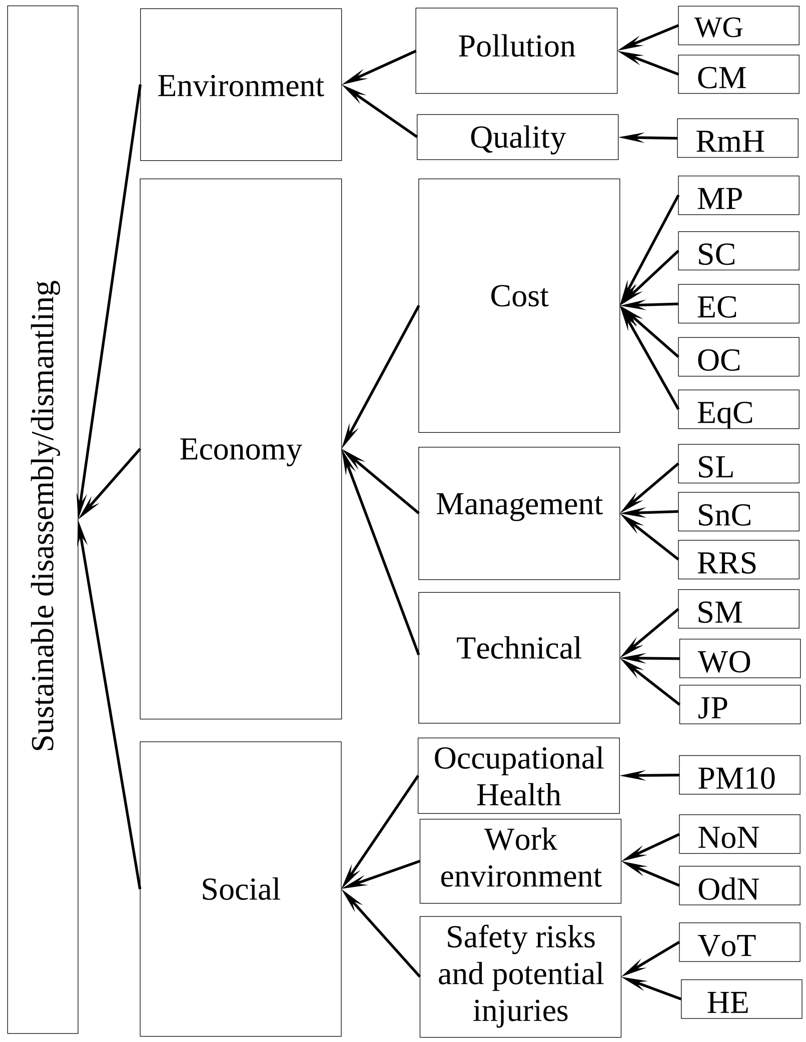

Figure 4-1 Sustainable disassembly/dismantling hierarchical structure

Management criteria includes three indicators which are: Safety level (SL) required for the workers depending on strategies requirements; Amount of Sorting and cleaning (SnC) activities to be done, before sending the material to recycling center; Rules, regulations, and standards (RRS) obliged to implement the strategies. Technical criteria supports: Necessity level of having Supervisor monitoring (SM) the work is done properly and in secure way; Need of a precise and serious Work outline (WO) before starting the process; Level of Job proficiency (JP) required for the labors before starting the job.

In terms of Social, working within the framework of each strategy may have influence on the: Amount of PM10 concentration (PM10)(Pirani et al., 2015); Level of potential Noise nuisance

(NoN)(Landström et al., 1995; Landström et al., 1990) and Odour nuisance (OdN)(Engen, 1986; Küller and Wetterberg, 1996); also working with Heavy hazardous equipment (HE) as well as Variety of tools (VoT) may increase the chance of injuries for the workers. These indicators further classified into main criteria according to Figure 4-1.

So far, the disassembly/dismantling strategies have been established. Also, the sustainability drivers based on TBL concept were meticulously determined. A framework, summarizing the upward steps followed in this study, is illustrated in Figure 4-2.

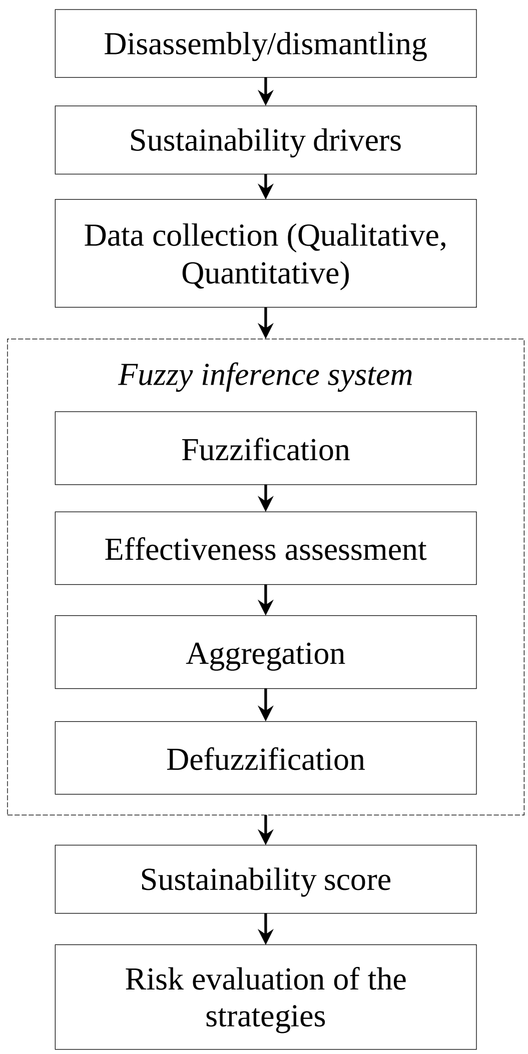

Figure 4-2 Research framework for the study

4.5 Sustainability assessment of the strategies

4.5.1 Data collection

The eight strategies were evaluated in terms of 19 indicators (Figure 4-1). Due to confidentiality issues, for this paper the realistic data was not provided. Also, for some indicators a quantitative measurement is not applicable (i.e. NoN, OdN, etc.); therefore, approximate measures or quantities can be used (Entzinger and Suzuki, 2010; Min et al., 2011).

In this study, approximate measures were associated with numerical scales (Table 4-1) to evaluate the indicators. Finally the evaluation scores of indicators in each strategy were determined by the judgments of three experts who were involved during the implementation of the eight strategies. Considering that all the experts' judgements were equally important, a homogeneous aggregation was performed on the obtained results from the experts. Table 4-2 represents the arithmetic average between the scores obtained from the experts.

4.5.2 Fuzzy inference system

Sustainability and sustainable development often involve complex and inexact indicators with a high degree of uncertainty due to incomplete understanding of underlying issues. For this reason, the theory of fuzzy logic has been proven to be a useful mathematical tool to handle vagueness and uncertainty, associated with human cognitive processes, such as thinking and reasoning (Zadeh, 1965). Such fuzzy inference can be implemented through the application of linguistic variables (Kaya, 2012; Kim et al., 2013; Simic, 2015; Zadeh, 1975).

In a linguistic variable, values are served in the form of words or sentences via the use of natural or artificial language. When the available data is too imprecise, application of linguistic variables (words) becomes a necessity rather than use of numbers. Even having precise data, while the system can tolerate a certain level of imprecision, computing with words, leads to achieve robustness and low solution cost for the system. In addition, since human brain is more familiar with words, application of such system results in better rapport with reality (Zadeh and Kacprzyk, 1999a, b). It also perfectly allows to operate both quantitative and qualitative data (Herrera et al., 2009; Kerre, 1982).

Linguistic variables are often characterized with fuzzy sets (Bellman and Zadeh, 1970; Kacprzyk and Yager, 2001; Liu et al., 2014; Sánchez-Lozano et al., 2015). Fuzzy sets are the extension of classical sets. In a classical set which known also as binary set or crisp set, an element belongs or doesn't belong to the set and represents as 1 or 0, respectively: a True-False concept. However, in a fuzzy set, all the elements or objects potentially belong to the set but with different grades of membership which usually is a real number between 0 and 1.

Table 4-1 Different scales for evaluation of indicators

Approximate measure	Numerical scale
Very Low	[0, 2)
Low	[2, 4)
Medium	[4, 6)
High	[6, 8)
Very High	[8, 10]

Table 4-2 Average scores obtained from the experts

Indicators	Strategies							
	A	B	C	D	E	F	G	H
WG	3.3	9.5	7.5	5	5	5	2.45	4
CM	2.1	0	0	2	3	2.5	2.75	2
RmH	9.5	0	1	3.5	4.5	5	7.5	6.5
MP	9.5	1	2.5	3	3.5	4.5	5.25	6
SC	1.5	6.5	6	5	4	3.5	1.5	4
EC	1.5	1	1	4.5	6.5	7	1.5	4
OC	7.5	1.5	2	3.5	5	5.75	6.5	6
EqC	7.3	1	1.5	2.5	3.5	4	5	6.5
SL	3	2	2	8.5	7	7	2.5	5
SnC	7	1	2	4.5	5.5	6.4	5	5.5

Table 4-2 Average scores obtained from the experts (continue)

RRS	2	1	1	3	3	3	1.5	3.5
SM	3	1.5	4	6	6.5	7	4.5	6
WO	0	0.5	3	4.5	6	6.9	5.5	6
JP	5.5	2	2	5	5.5	6.5	5	6
PM10	3.5	2.5	2	7	7.5	8.5	3.5	5
NoN	6.5	4	4	7.5	8.5	9	5.5	5.75
OdN	2.5	2	2	5.5	5	5	2.5	2.5
VoT	7.5	0.5	1	1.5	2.5	3	6.5	8.5
HE	2.8	5	5	8	7.4	7.4	3	5

Within this statement, fuzzy set *A* in a universe of discourse *X* is described by membership function μ_A that assigns a value between 0 and 1 to every element *x* in the universe. Eq. (4-1) represents the corresponding relation.

$$A = \{ \mu_A(x) \mid x \in X , \mu_A(x) \in [0, 1]\}; \tag{4-1}$$

In practical applications, triangular and trapezoid membership functions are most commonly used by researchers in theory and practice. Triangular fuzzy numbers (TFNs) are more practical in application due to the easiness in calculation and simpleness of features (Ko, 2013; Li et al., 2013; Liu et al., 2013; Mirshams et al., 2014; Shen et al., 2013). A TFN in this study was detonated as a triplet (*a*, *b*, *c*); where *a*, *b*, and *c* were denoted as: the smallest possible value, the most promising value, and the highest possible value that describe a fuzzy event, respectively (Figure 4-3). Calculation of corresponding membership value for each element x is done using Eq. (4-2). Readers may refer to Zimmermann (1996) for a thorough treatise on fuzzy numbers as well as the arithmetic operations on them.

$$\mu_A(x|A) = \begin{cases} 0, & x < a; \\ \frac{x-a}{b-a}, & a \le x \le b; \\ \frac{c-x}{c-b}, & b \le x \le c; \\ 0, & x > c; \end{cases} \tag{4-2}$$

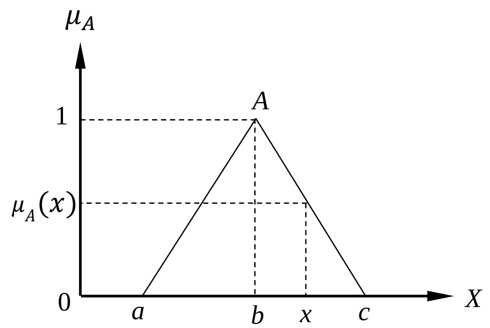

Figure 4-3 Triangular fuzzy number *A*

Five triangular fuzzy sets have been considered for effectiveness assessment of the indicators (Figure 4-4 and Table 4-3). Consequently based on the data in Table 4-2, the fuzzy effectiveness assessments of the indicators for every strategy were calculated according to the acquired degrees of membership (Table 4-4). The results were finally summarized in Table 4-5.

In this study, equal relative weights for criteria and indicators were agreed. All the indicators except RmH and MP have negative characteristics; which it means the lower is the score for these indicators, the better. To make all the scores homogeneous, for RmH and MP indicators, the scores corresponding to them were vertically flipped. Through aggregation of the scores, the final fuzzy score for each strategy can be determined.

Fuzzy numbers are not straightforward to compare; therefore, for various trade-off analysis and management purposes, a *defuzzification* technique is required. Yager (1980) proposed a simple and popular *defuzzification* technique based on estimation of center of gravity (COG) for the fuzzy number. COG has been commonly used in different applications as a *defuzzification* method (Ebrahimnejad et al., 2012; González et al., 2002; Khan et al., 2002; Liu et al., 2012).

First, the centroid point for the area under the fuzzy number is determined. Then, the *defuzzified* value corresponds to $\bar{x}_0$: which is the horizontal axis coordinate of the centroid point (Eq. (4-3)).

$$\bar{x}_0 = \frac{\int x\, \mu_A(x) dx}{\int \mu_A(x) dx}; \tag{4-3}$$

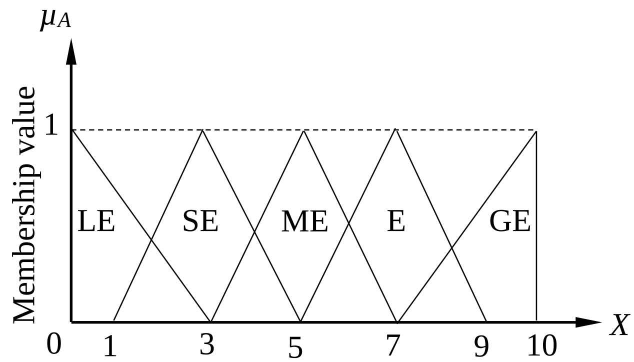

Figure 4-4 Graphic representation of fuzzy sets

Table 4-3 Fuzzy sets for effectiveness assessment of indicators

Linguistic values	TFNs
Least effective (LE)	(0, 0, 2)
Slightly effective (SE)	(1, 3, 5)
Moderately effective (ME)	(3, 5, 7)
Effective (E)	(5, 7, 9)
Greatly effective (GE)	(8, 10, 10)

Table 4-4 Degrees of membership for fuzzy assessment of indicators

Indicators	Strategies							
	A	B	C	D	E	F	G	H
WG	0.875SE 0.125ME	0.833GE	0.167GE 0.75E	1.0ME	1.0ME	1.0ME	0.275LE 0.725SE	0.5SE 0.5ME
CM	0.563SE 0.292LE	1.0LE	1.0LE	0.33LE 0.50SE	1.0SE	0.75SE 0.25LE	0.125LE 0.825SE	0.33LE 0.50SE
RmH	0.833GE	1.0LE	0.67LE	0.25ME 0.75SE	0.25SE 0.75ME	1.0ME	0.167GE 0.75E	0.25ME 0.75E
MP	0.833GE	0.67LE	0.75SE 0.25LE	1.0SE	0.25ME 0.75SE	0.25SE 0.75ME	0.125E 0.825ME	0.5ME 0.5E
SC	0.25SE 0.50LE	0.25ME 0.75E	0.5ME 0.5E	1.0ME	0.5ME 0.5SE	0.25ME 0.75SE	0.25SE 0.50LE	0.5ME 0.5SE

Table 4-4 Degrees of membership for fuzzy assessment of indicators (continue)

EC	0.25SE 0.50LE	0.67LE	0.67LE	0.25SE 0.75ME	0.25ME 0.75E	1.0E	0.25SE 0.50LE	0.5ME 0.5SE
OC	0.167GE 0.75E	0.25SE 0.50LE	0.33LE 0.50SE	0.25ME 0.75SE	1.0ME	0.375E 0.625ME	0.25ME 0.75E	0.5ME 0.5E
EqC	0.083GE 0.875E	0.67LE	0.25SE 0.50LE	0.25LE 0.75SE	0.25ME 0.75SE	0.5ME 0.5SE	1.0ME	0.25ME 0.75E
SL	1.0SE	0.33LE 0.50SE	0.33LE 0.50SE	0.25E 0.50GE	1.0E	1.0E	0.25LE 0.75SE	1.0ME
SnC	1.0E	0.67LE	0.33LE 0.50SE	0.25SE 0.75ME	0.25E 0.75ME	0.3ME 0.7E	1.0ME	0.25E 0.75ME
RRS	0.33LE 0.50SE	0.67LE	0.67LE	1.0SE	1.0SE	1.0SE	0.25SE 0.50LE	0.25ME 0.75SE
SM	1.0SE	0.25SE 0.50LE	0.5ME 0.5SE	0.5ME 0.5E	0.25ME 0.75E	1.0E	0.25SE 0.75ME	0.5ME 0.5E
WO	1.0LE	0.833LE	1.0SE	0.25SE 0.75ME	0.5ME 0.5E	0.05ME 0.95E	0.25E 0.75ME	0.5ME 0.5E
JP	0.25E 0.75ME	0.33LE 0.50SE	0.33LE 0.50SE	1.0ME	0.25E 0.75ME	0.25ME 0.75E	1.0ME	0.5ME 0.5E
PM10	0.25ME 0.75SE	0.25LE 0.75SE	0.33LE 0.50SE	1.0E	0.167GE 0.75E	0.25E 0.50GE	0.25ME 0.75SE	1.0ME
NoN	0.25ME 0.75E	0.5ME 0.5SE	0.5ME 0.5SE	0.167GE 0.75E	0.25E 0.50GE	0.667GE	0.25E 0.75ME	0.375E 0.625ME
OdN	0.25LE 0.75SE	0.33LE 0.50SE	0.33LE 0.50SE	0.25E 0.75ME	1.0ME	1.0ME	0.25LE 0.75SE	0.25LE 0.75SE
VoT	0.75E 0.167GE	0.833LE	0.67LE	0.25SE 0.50LE	0.25LE 0.75SE	1.0SE	0.25ME 0.75E	0.25E 0.50GE
HE	0.083LE 0.875SE	1.0ME	1.0ME	0.50E 0.333GE	0.133GE 0.8E	0.133GE 0.8E	1.0SE	1.0ME

4.6 Evaluation of the strategies in different risk scenarios

In terms of sustainability, selecting the appropriate strategy to employ depends on different risk scenarios that we may confront. Risk scenarios refer to the level of influence about the three sustainability aspects (environment, economy, and social).

Table 4-5 Fuzzy effectiveness assessment of the indicators for the strategies

Indicators	Strategies							
	A	B	C	D	E	F	G	H
WG	(1.25, 3.25, 5.25)	(5.831, 8.33, 8.33)	(4.919, 6.92, 8.42)	(3, 5, 7)	(3, 5, 7)	(3, 5, 7)	(0.725, 2.175, 4.45)	(2, 4, 6)
CM	(0.563, 1.689, 3.69)	(0, 0, 3)	(0, 0, 3)	(0.5, 1.5, 3.499)	(1, 3, 5)	(0.75, 2.25, 4.5)	(0.875, 2.625, 4.75)	(0.5, 1.5, 3.499)
RmH	(5.831, 8.33, 8.33)	(0, 0, 3)	(0, 0, 2.001)	(1.5, 3.5, 5.5)	(2.5, 4.5, 6.5)	(3, 5, 7)	(4.919, 6.92, 8.42)	(4.5, 6.5, 8.5)
MP	(5.831, 8.33, 8.33)	(0, 0, 2.001)	(0.75, 2.25, 4.5)	(1, 3, 5)	(1.5, 3.5, 5.5)	(2.5, 4.5, 6.5)	(7.225, 9.125, 9.375)	(4, 6, 8)
SC	(0.25, 0.75, 2.75)	(4.5, 6.5, 8.5)	(4, 6, 8)	(3, 5, 7)	(2, 4, 6)	(1.5, 3.5, 5.5)	(0.25, 0.75, 2.75)	(2, 4, 6)
EC	(0.25, 0.75, 2.75)	(0, 0, 2.001)	(0, 0, 2.001)	(2.5, 4.5, 6.5)	(4.5, 6.5, 8.5)	(5, 7, 9)	(0.25, 0.75, 2.75)	(2, 4, 6)
OC	(4.919, 6.92, 8.42)	(0.25, 0.75, 2.75)	(0.5, 1.5, 3.499)	(1.5, 3.5, 5.5)	(3, 5, 7)	(3.75, 5.75, 7.75)	(4.5, 6.5, 8.5)	(4, 6, 8)
EqC	(4.956, 6.955, 8.705)	(0, 0, 2.001)	(0.25, 0.75, 2.75)	(0.75, 2.25, 4.5)	(1.5, 3.5, 5.5)	(2, 4, 6)	(3, 5, 7)	(4.5, 6.5, 8.5)
SL	(1, 3, 5)	(0.5, 1.5, 3.499)	(0.5, 1.5, 3.499)	(4.75, 6.75, 7.25)	(0.5, 0.7, 0.9)	(5, 7, 9)	(0.75, 2.25, 4.5)	(3, 5, 7)
SnC	(5, 7, 9)	(0, 0, 2.001)	(0.5, 1.5, 3.499)	(2.5, 4.5, 6.5)	(3.5, 5.5, 7.5)	(4.4, 6.4, 8.4)	(3, 5, 7)	(3.5, 5.5, 7.5)
RRS	(0.5, 1.5, 3.499)	(0, 0, 2.001)	(0, 0, 2.001)	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)	(0.25, 0.75, 2.75)	(1.5, 3.5, 5.5)
SM	(1, 3, 5)	(0.25, 0.75, 2.75)	(2, 4, 6)	(4, 6, 8)	(4.5, 6.5, 8.5)	(5, 7, 9)	(2.5, 4.5, 6.5)	(4, 6, 8)
WO	(0, 0, 3)	(0, 0, 2.499)	(1, 3, 5)	(2.5, 4.5, 6.5)	(4, 6, 8)	(4.9, 6.9, 8.9)	(3.5, 5.5, 7.5)	(4, 6, 8)
JP	(3.5, 5.5, 7.5)	(0.5, 1.5, 3.499)	(0.5, 1.5, 3.499)	(3, 5, 7)	(3.5, 5.5, 7.5)	(4.5, 6.5, 8.5)	(3, 5, 7)	(4, 6, 8)
PM10	(1.5, 3.5, 5.5)	(0.75, 2.25, 4.5)	(0.5, 1.5, 3.499)	(0.5, 0.7, 0.9)	(4.919, 6.92, 8.42)	(4.75, 6.75, 7.25)	(1.5, 3.5, 5.5)	(3, 5, 7)
NoN	(4.5, 6.5, 8.5)	(2, 4, 6)	(2, 4, 6)	(4.919, 6.92, 8.42)	(4.75, 6.75, 7.25)	(4.669, 6.67, 6.67)	(3.5, 5.5, 7.5)	(3.75, 5.75, 7.75)
OdN	(0.75, 2.25, 4.5)	(0.5, 1.5, 3.499)	(0.5, 1.5, 3.499)	(3.5, 5.5, 7.5)	(3, 5, 7)	(3, 5, 7)	(0.75, 2.25, 4.5)	(0.75, 2.25, 4.5)
VoT	(4.919, 6.92, 8.42)	(0, 0, 2.499)	(0, 0, 2.001)	(0.25, 0.75, 2.75)	(0.75, 2.25, 4.5)	(1, 3, 5)	(4.5, 6.5, 8.5)	(4.75, 6.75, 7.25)
HE	(0.875, 2.625, 4.624)	(3, 5, 7)	(3, 5, 7)	(4.831, 6.83, 7.83)	(4.931, 6.93, 8.53)	(4.931, 6.93, 8.53)	(1, 3, 5)	(3, 5, 7)

In Table 4-6, are shown different scenarios that have been taken into account for this work accompanied by their descriptions. For example in scenario Baseline (BL), the three sustainability elements have the same risk; while, Scenario 3 (SC3) has a higher risk for environment. Thus, analyzing SC3, a higher relative weight might be allocated to environment. The ratio for each scenario is defined by three numbers as: “environment:economy:social”.

According to the methodology described in Section 4.4, the sustainability score for each strategy depending on the risk scenarios were calculated. The final results are tabulated in Table 4-7. Also a ranking associated to each strategy for every scenario was established.

Table 4-6 Different sustainability scenarios

Scenario	Description	Ratio
Baseline (BL)	Equal risk for environment, economy, and social	1:1:1
Scenario 1 (SC1)	Low risk for environment	1:2:2
Scenario 2 (SC2)	Medium risk for environment	2:1:1
Scenario 3 (SC3)	High risk for environment	3:1:1
Scenario 4 (SC4)	Low risk for economy	2:1:2
Scenario 5 (SC5)	Medium risk for economy	1:2:1
Scenario 6 (SC6)	High risk for economy	1:3:1
Scenario 7 (SC7)	Low risk for social	2:2:1
Scenario 8 (SC8)	Medium risk for social	1:1:2
Scenario 9 (SC9)	High risk for social	1:1:3

The results showed that, in BL scenario where all the aspects have equal risk, *Strategy B* is the best alternative, closely followed by *Strategy C*. This is due to the fact that these two strategies have a very low impact of social and economy factors. Very few operational costs and non-labor intensive activities are needed; while, the quality of alloys is compromised. However, having higher risk of environment, more efforts should be put to retrieve a higher quality of alloys. In Scenario 2 and 3 (SC2 and SC3), the rankings benefit *Strategy A* as the first and *Strategy G* as the second choice.

Within the assayed scenarios, *Strategies D*, *E*, and *F* were never selected as the top ranked alternatives. These results can be a clue to the industry partner to eliminate or revise them for further optimization. These strategies are mainly cutting based, and it seems that the amount of tools and efforts spent during their implementations make them not economically, socially, and environmentally viable.

On the contrary, *Strategies A*, *B*, *C*, and *G* are the most active alternatives in different risk scenarios. These strategies can be distinguished from the rest because they meet strong points as economic and social feasibility in *B* and *C* as well as environment viability in *A* and *G*.

Figure 4-5 illustrates the ranking variation of strategies in different scenarios.

4.7 Conclusion and further studies

End-of-life aircrafts are recognized as valuable sources of aluminum and different materials. However, the use of different alloy families and the complex structure of the carcass have brought difficulties into the recyclability process. Unlike previous works, this research proposes for first time a practical methodology focused on categorization and sorting of alloys into their family series before sending to recycling centers. Eight disassembly/dismantling strategies have been evaluated in terms of sustainability and sustainable development. The strategies had been implemented on a Bombardier Regional Jet aircraft. 19 indicators were defined to assess the environmental, social, and economic impacts of each strategy. The input data were provided from the experts who were engaged into the strategies implementation. A fuzzy inference system was applied to handle the uncertainties and vagueness existent in the nature of the indicators.

With the goal to have a robust understanding about the sustainability performance of each strategy, ten different risk scenarios were taken into account. The risk is associated to the influence of the three bottom line aspects. The results showed that in environmental risky situations, *Systematic disassembly* and *Smart disassembly* are the alternatives of preference; while in economic and social risky scenarios, *Shredding* and *Smart shredding* are the ones desired, respectively.

Table 4-7 Final sustainability scores and rankings of strategies for every scenario

Strategies	BL		SC1		SC2		SC3		SC4		SC5		SC6		SC7		SC8		SC9	
	COG	Ranking	COG	Ranking	COG	Ranking	COG	Ranking	COG	Ranking	COG	Ranking	COG	Ranking	COG	Ranking	COG	Ranking	COG	Ranking
A	3.48	3	3.66	4	3.26	1	3.12	1	3.45	1	6.95	4	3.53	3	3.33	1	3.67	4	3.79	4
B	3.41	1	3.00	1	3.92	4	4.22	5	3.69	4	5.39	1	2.85	1	3.54	3	3.25	2	3.16	2
C	3.46	2	3.10	2	3.91	3	4.17	4	3.63	3	5.39	2	3.12	2	3.65	4	3.23	1	3.09	1
D	4.87	6	5.00	6	4.70	6	4.60	6	4.89	6	9.34	6	4.82	6	4.71	6	5.07	6	5.19	6
E	5.16	8	5.31	7	4.96	8	4.84	8	5.10	8	9.73	8	5.26	7	5.05	7	5.29	8	5.36	8
F	5.14	7	5.35	8	4.87	7	4.71	7	5.01	7	9.72	7	5.41	8	5.06	8	5.24	7	5.30	7
G	3.50	4	3.65	3	3.32	2	3.21	2	3.47	2	6.86	3	3.57	4	3.39	2	3.65	3	3.74	3
H	4.39	5	4.65	5	4.06	5	3.86	3	4.23	5	8.53	5	4.71	5	4.28	5	4.52	5	4.60	5

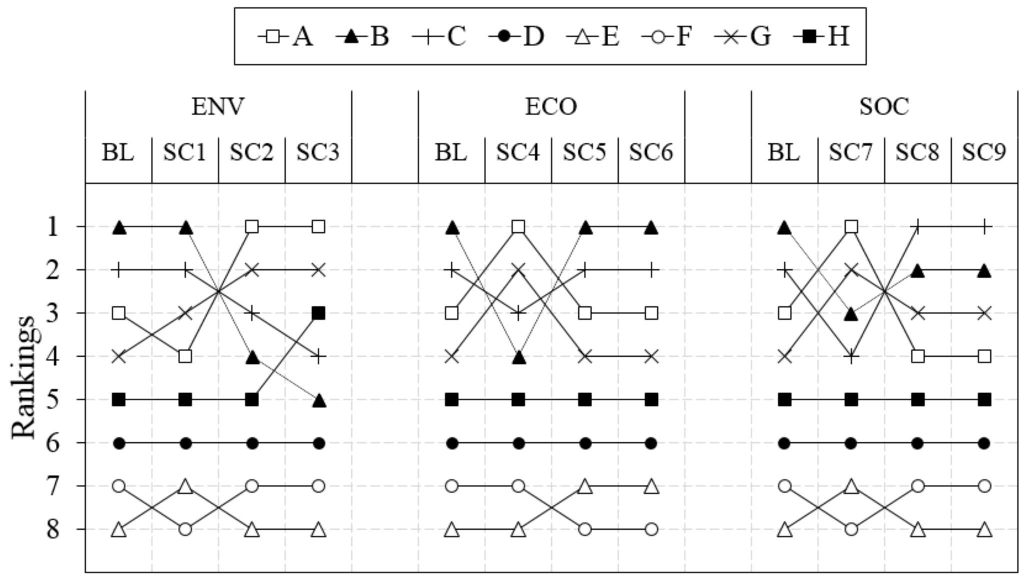

Figure 4-5 Ranking fluctuations in different scenarios

The results for this paper were obtained based on equal relative weights for the indicators and criteria. Useful techniques such as Analytic hierarchy process can be helpful to perform a more accurate evaluation of the strategies. Simultaneously, using quantitative data as the input can improve the reliability in selection of the best disassembly/dismantling strategy in different risk scenarios.

This study can be applied in other real case-study problems to determine the most appropriate solution based on the current liability and interests of the managers, decision-makers, and policy-makers in the company.

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4.9 REFERENCES

Airbus, S.A.S., 2008. Process for advanced management of end-of-life of aircraft (PAMELA), France.

An, T., Huang, Y., Li, G., He, Z., Chen, J., Zhang, C., 2014. Pollution profiles and health risk assessment of VOCs emitted during e-waste dismantling processes associated with different dismantling methods. *Environment International 73*, 186-194.

Asmatulu, E., Overcash, M., Twomey, J., 2013a. Recycling of aircraft: State of the art in 2011. *Journal of Industrial Engineering*, 1-8.

Asmatulu, E., Twomey, J., Overcash, M., 2013b. Evaluation of recycling efforts of aircraft companies in Wichita. Resources, *Conservation and Recycling 80*, 36-45.

Bellman, R.E., Zadeh, L.A., 1970. Decision-Making in a Fuzzy Environment. *Management Science 17*, 141-164.

CRIAQ-ENV412, Process for advanced management and technologies of aircraft end-of-life, http://www.polymtl.ca/env412/index.php.

Das, S.K., Kaufman, J.G., 2008. Recycling aluminum aerospace alloys. *Light Metals, TMS 1161-1165*.

Dursun, M., Karsak, E.E., Karadayi, M.A., 2011. Assessment of health-care waste treatment alternatives using fuzzy multi-criteria decision making approaches. *Resources, Conservation and Recycling 57*, 98-107.

Ebrahimnejad, S., Mousavi, S.M., Tavakkoli-Moghaddam, R., Hashemi, H., Vahdani, B., 2012. A novel two-phase group decision making approach for construction project selection in a fuzzy environment. *Applied Mathematical Modelling 36*, 4197-4217.

Engen, T., 1986. Perception of odor and irritation. *Environment International 12*, 177-187.

Entzinger, J.O., Suzuki, S., 2010. Modeling of the visual approach to landing using neural networks and fuzzy supervisory control. *Aerospace Science and Technology 14*, 118-125.

Frosch, R.A., Gallopoulos, N.E., 1989. Strategies for Manufacturing. *Scientific American 261*, 144-152.

Gaustad, G., Olivetti, E., Kirchain, R., 2012. Improving aluminum recycling: A survey of sorting and impurity removal technologies. *Resources, Conservation and Recycling 58*, 79-87.

González, B., Adenso-Díaz, B., González-Torre, P.L., 2002. A fuzzy logic approach for the impact assessment in LCA. *Resources, Conservation and Recycling 37*, 61-79.

Grimes, S., Donaldson, J., Gomez, G.C., 2008. *Report on the environmental benefits of recycling*. Bureau of International Recycling (BIR), Imperial College London: Centre for Sustainable Production & Resource Efficiency (CSPRE).

Herrera, F., Alonso, S., Chiclana, F., Herrera-Viedma, E., 2009. Computing with words in decision making: foundations, trends and prospects. *Fuzzy Optimization and Decision Making 8*, 337-364.

Jayal, A.D., Badurdeen, F., Dillon Jr, O.W., Jawahir, I.S., 2010. Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. *CIRP Journal of Manufacturing Science and Technology 2*, 144-152.

Kacprzyk, J., Yager, R.R., 2001. Linguistic summaries of data using fuzzy logic. *International Journal of General Systems 30*, 133-154.

Kaya, İ., 2012. Evaluation of outsourcing alternatives under fuzzy environment for waste management. *Resources*, *Conservation and Recycling 60*, 107-118.

Kerre, E.E., 1982. The use of fuzzy set theory in electrocardiological diagnostics. *Approximate reasoning in decision analysis*, 277-282.

Khan, F.I., Sadiq, R., Husain, T., 2002. GreenPro-I: a risk-based life cycle assessment and decision-making methodology for process plant design. *Environmental Modelling & Software 17*, 669-692.

Kim, Y., Chung, E.-S., Jun, S.-M., Kim, S.U., 2013. Prioritizing the best sites for treated wastewater instream use in an urban watershed using fuzzy TOPSIS. *Resources, Conservation and Recycling 73*, 23-32.

Ko, Y.-T., 2013. Optimizing product architecture for complex design. *Concurrent Engineering 21*, 87-102.

Kohut, R., 2003. The long-term effects of carbon dioxide on natural systems: issues and research needs. *Environment International 29*, 171-180.

Küller, R., Wetterberg, L., 1996. The subterranean work environment: Impact on well-being and health. *Environment International 22*, 33-52.

Lambert, A.F., Gupta, S.M., 2004. *Disassembly modeling for assembly, maintenance, reuse and recycling (vol. 19)*. Boca Raton: CRC press.

Landström, U., Åkerlund, E., Kjellberg, A., Tesarz, M., 1995. Exposure levels, tonal components, and noise annoyance in working environments. *Environment International 21*, 265-275.

Landström, U., Löfstedt, P., Åkerlund, E., Kjellberg, A., Wide, P., 1990. Noise and annoyance in working environments. *Environment International 16*, 555-559.

Li, Z., Huang, G., Zhang, Y., Li, Y., 2013. Inexact two-stage stochastic credibility constrained programming for water quality management. *Resources, Conservation and Recycling 73*, 122-132.

Liu, H.-C., Liu, L., Liu, N., Mao, L.-X., 2012. Risk evaluation in failure mode and effects analysis with extended VIKOR method under fuzzy environment. *Expert Systems with Applications 39*, 12926-12934.

Liu, H.-C., Wu, J., Li, P., 2013. Assessment of health-care waste disposal methods using a VIKOR-based fuzzy multi-criteria decision making method. *Waste management 33*, 2744-2751.

Liu, J., Li, Y.P., Huang, G.H., Zeng, X.T., 2014. A dual-interval fixed-mix stochastic programming method for water resources management under uncertainty. *Resources, Conservation and Recycling 88*, 50-66.

Mascle, C., Baptiste, P., Sainte-Beuve, D., Camelot, A., 2015. Process for advanced management and technologies of aircraft EOL. *Procedia CIRP 26*, 299-304.

Min, C.-o., Lee, D.-w., Cho, K.-r., Jo, S.-j., Yang, J.-s., Lee, W.-b., 2011. Control of approach and landing phase for reentry vehicle using fuzzy logic. *Aerospace Science and Technology 15*, 269-282.

Mirshams, M., Naseh, H., Fazeley, H.R., 2014. Multi-objective multidisciplinary design of Space Launch System using Holistic Concurrent Design. *Aerospace Science and Technology 33*, 40-54.

Pirani, M., Best, N., Blangiardo, M., Liverani, S., Atkinson, R.W., Fuller, G.W., 2015. Analysing the health effects of simultaneous exposure to physical and chemical properties of airborne particles. *Environment International 79*, 56-64.

Sánchez-Lozano, J.M., Serna, J., Dolón-Payán, A., 2015. Evaluating military training aircrafts through the combination of multi-criteria decision making processes with fuzzy logic. A case study in the Spanish Air Force Academy. *Aerospace Science and Technology 42*, 58-65.

Shen, L., Olfat, L., Govindan, K., Khodaverdi, R., Diabat, A., 2013. A fuzzy multi criteria approach for evaluating green supplier's performance in green supply chain with linguistic preferences. *Resources, Conservation and Recycling 74*, 170-179.

Simic, V., 2015. A two-stage interval-stochastic programming model for planning end-of-life vehicles allocation under uncertainty. *Resources, Conservation and Recycling 98*, 19-29.

Yager, R.R., 1980. On choosing between fuzzy subsets. *Kybernetes 9*, 151-154.

Zadeh, L.A., 1965. Fuzzy sets. *Information and Control 8*, 338-353.

Zadeh, L.A., 1975. The concept of a linguistic variable and its application to approximate reasoning—I. *Information Sciences 8*, 199-249.

Zadeh, L.A., Kacprzyk, J., 1999a. *Computing with words in Information/Intelligent systems 1: Foundations* (vol. 33). Physica-Verlag (Springer-Verlag), Heidelberg, New York.

Zadeh, L.A., Kacprzyk, J., 1999b. *Computing with words in Information/Intelligent systems 2: Applications* (vol. 34). Physica-Verlag (Springer-Verlag), Heidelberg, New York.

Zimmermann, H.J., 1996. *Fuzzy set theory-and its applications*, 3rd ed. Kluwer Academic Publishers, Boston.

CHAPTER 5 ARTICLE 3: SUSTAINABILITY ASSESSMENT USING FUZZY-INFERENCE TECHNIQUE (SAFT): A METHODOLOGY TOWARD GREEN PRODUCTS

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5.1 ABSTRACT

Green products are increasingly becoming the center of attention for policy and decision makers worldwide not only because of environmental and eco-systems crisis but also to satisfy the current competitiveness in the markets. With this aim, it is highly attractive to count with mathematical tools that allow to assess the sustainability of the products. In this regard, fuzzy techniques have been broadly used in different studies due to uncertainty and vagueness associated with sustainability problems. However, these studies are mostly based on fuzzy rules generation which is time consuming and also can lead to redundancy and inaccuracy. In this study, we introduced a fuzzy-inference system to evaluate product/process sustainability (SAFT). The proposed method does not require generation of rules which simplifies the procedure and makes it more precise. Furthermore, fuzzy analytic hierarchy process accompanied by Shannon's entropy formula was employed to determine the relative importance of each element in the hierarchy. The methodology SAFT was compared with fuzzy rule-base technique and impressively pretty the same results were obtained. The method introduced in this paper was built as a user interface platform which can be used as a fuzzy expert system to facilitate the sustainability assessment of products/processes in different manufacturing industries.

Key words: Sustainability index; Green product; Sustainable development; Fuzzy expert system; Shannon's Entropy; Fuzzy AHP

5.2 Introduction

Over the past decades, sustainability and sustainable development are more and more becoming the hot topics among the managers of every organization, not only because of environmental and eco-systems crisis but also to keep in touch with the competitiveness in the markets. There are obvious evidences showing current product/process development is unsustainable: Ozone depletion, global warming, extinction of species, poverty, economic crisis, social and political unrest, violence, etc.

Sustainable development is a pathway towards sustainability which introduced a new paradigm for product/service/process development. This concept has triggered a wide variety of definitions and interpretations for sustainable development. In the literature, various researchers/organizations have published their own definitions about sustainable development which shows how they put sustainability in action, depending on their goals (Table 5-1).

A survey done by European Design Council 2001 showed that around 87% of the companies in Europe believe in sustainable development as a great opportunity, and not a cost burden (Curtis and Walker, 2001). The advantages associated with sustainable development include: satisfaction of customer needs, expand marketing with new possibilities, increase economic success chances, augmentation of creativity and innovation in product/design development, alleviation of environmental issues, etc.

With this current increasing attention about sustainability and sustainable development, it is not surprising that a quantifiable sustainability rating would one day be required for all the manufactured products via some obligatory regulations (like energy efficiency labeling for electronic appliances). Quantifying sustainability refers to the use of mathematical techniques to analyze the impact of products on environment, social, and economy. Thus, the sustainable effect of products upon life-cycle will be translated into numbers that are intelligible for the designers, manufacturers, managers, etc. To count with such a rating system, it will not only add value to the products, but also widen the perspective of the designers towards more sustainable products. For example the use of nanotechnology potentially will bring a lot of benefits to improve human's life quality, but still there are numerous challenges facing the assessment of a sustainable nanotechnology (Meyer and Upadhyayula, 2014).

Table 5-1 Definitions of sustainable development

Goal	Definition
Ecological preservation	"Development that is likely to achieve lasting satisfaction of human needs and improvement of the quality of human life" (Allen, 1980).
Biodiversity conservation	Sustainable development is about: "Maintenance of essential ecological processes and life support systems", "Preservation of genetic diversity", and "Sustainable utilization of species and ecosystems" (IUCN, 1980).
Intergeneration equity	"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).
Environment regulatory consensus	"Sustainable development argues for: (1) development subject to a set of constraints which set resource harvest rates at levels not higher than managed natural regeneration rate, and (2) use of the environment as a "waste sink" on the basis that waste disposal rates should exceed rates of managed or natural assimilative capacity of the ecosystem" (Pearce, 1988).
Eco-business vision	"Sustainable development recognizes economic growth and environmental protection as are inextricably linked, and that the quality of present and future life rests on meeting basic human needs without destroying the environment upon which all life depends" (Schmidheiny, 1992).
Political consensus	"Sustainable development involves a process of deep and profound change in the political, social, economic, institutional and technological order including redefinition of relations between developing and more developed countries" (Strong, 1992).
Business interest	"Sustainable development means basing developmental and environmental policies on a comparison of costs and benefits and on careful economic analysis that will strengthen environmental protection and lead to rising and sustainable levels of welfare" (WorldBank, 1992).
Marketing perspective	"Balancing social, ethical and environmental issues alongside economic factors within the product or service development process to ensure that the needs of both the business customer and society are met while protecting the ecosystem" (Curtis and Walker, 2001).
Technology innovation	"Sustainable development relates to economical, ecological and social developments. Possibilities to co-optimize these developments depend strongly on the availability of technologies, innovation strategies, and the institutional conditions that are set by government policies" (Vollenbroek, 2002).

The present work aims to develop a suitable methodology for product sustainability evaluation considering the environmental, economic, and social risks/impacts of the products upon life-cycle. To deal with uncertainty and fuzziness associated with sustainability problems, fuzzy techniques were applied. The methodology sustainability assessment using fuzzy-inference technique (SAFT) was successfully validated and compared with the results from the literature that used fuzzy rule-base technique.

Including this introduction, Section 5.3 provides a critical review of the state of the art; in Section 5.4, the sustainability hierarchy, theory of fuzzy sets and definitions are presented; the proposed methodology and the practical implementation are described in Section 5.5; The results from the comparison with fuzzy rule-base method and the developed user interface platform for the tool are discussed in Section 5.6; finally the conclusion is given in Section 5.7.

5.3 Literature review

One of the important steps for achieving sustainability in the scope of product manufacturing is to control the environmental, economic, and social impacts of the products (Hu and Bidanda, 2009; Lin et al., 2015; Vinodh and Rathod, 2010; Zhang et al., 2012). To this aim, there are plenty of databases, methodologies, and tools that have been developed to help designers to evaluate the impact of processes or manufactured products during their life-cycle. These tools are generally known as life-cycle assessment (LCA): methodological frameworks which are usually generalized and mostly concentrated on environmental aspect only. In addition, in conducting an LCA, usually the design and development phase of the product is excluded (Lee et al., 1995; Rebitzer et al., 2004); while the decisions in this phase can significantly influence the impacts of the product in subsequent life-cycle phases. Moreover, LCA techniques are data intensive and require considerable resources (time, labor, cost, etc.), which may not be justifiable in some cases (Hur et al., 2005; Khan et al., 2004).

In terms of design and development, Hallstedt (2016) presented an approach to identify proper sustainability criteria and categorize them into different life-cycle phases. eco-design techniques are another way that designers can use to reduce the environmental impact of their new products at the early stage of design (Bovea and Pérez-Belis, 2012; Knight and Jenkins, 2009). Eco-design techniques include guidelines, checklists, and MET (Material, Energy, and Toxicity) matrix. However, these techniques are not widely adopted by industries since they are not generic and require specific forms of customization prior to use. Hur et al. (2005) proposed a simplified LCA method integrated with eco-design techniques for a rapid sustainability assessment of Electrical and Electronic Equipment at the early stage of design. Although the method is faster than a detailed LCA, the application of the method for different product categories is compromised. Furthermore, the method solely focuses on environmental aspect.

However, focusing on environmental requirements only, causes more design constraints and consequently increase of costs (Kaebernick et al., 2002; Liu, 2009). Yet, the ultimate objective of sustainable development is the fully integration of environment, economic, and social aspects into an equilibrium (Santoyo-Castelazo and Azapagic, 2014; Vinodh and Joy, 2012; Vollenbroek, 2002). This requires a paradigm transition in current traditional design methodologies, manufacturing practices, and even educational curriculum in order to be more effective for applications built for sustainable futures (Jawahir et al., 2007).

Product sustainability index (PSI) was developed by Ford of Europe as a management tool in order to translate the sustainability aspects of products to the organization of vehicle product development (Schmidt and Butt, 2006). Although it is mentioned that the three environmental, social, and economic aspects have been covered, the study is more concentrated on environmental and economic zones. Besides, there is a lack of proper data normalization and weight allocation that can influence the final results. Ungureanu et al. (2007) used a scoring system, to evaluate the level of sustainability of manufactured products by taking into account some contributing sustainability elements.

Later, Zhang et al. (2012) performed a hierarchical structure to establish product sustainability index (ProdSI) based on Ungureanu et al. (2007) study. Using a hierarchical structure, ProdSI was divided into the main sustainability aspects (environment, economy, social), and each aspect subdivided into its sub-elements. Sub-elements are then measured via the generated metrics for each individual. Afterward, a simple 0 to 10 data-scaling method have been used accompanied by equal relative weightings to elements and sub-elements. Finally an aggregation was done to obtain the final sustainability index. Similarly, Mayyas et al. (2013) proposed a sustainability scoring model with eco-material selection approach in an automotive case study. Yu et al. (2007) used a decision-making algorithm based on analytical hierarchy process (AHP) and integrated assessment of environmental and economic performance of chemical products. The results of the study provided some initial guidelines for basic judgment about feasibility of using a certain product.

Sustainability problems are usually difficult to manage due to the presence of complexity along with a series of uncertainties and vagueness (Chen et al., 2015). Besides, combination of qualitative and quantitative data regarding the sustainability parameters makes the evaluation more complicated (Rostamzadeh et al., 2015). As a result it is sometimes very difficult to define sustainable development using mathematical terms. An approach to cope with this problem would be the application of a fuzzy inference system (Andriantiatsaholiniaina et al., 2004; Canavese and Ortega, 2013; Canavese et al., 2014; Hemdi et al., 2013; Phillis and Andriantiatsaholiniaina, 2001; Sabaghi et al., 2015a).

Fuzzy AHP was employed by different researchers to handle inconsistencies exist in experts' judgments (Bruno et al., 2015; Fan et al., 2016; Mardani et al., 2015). Tan et al. (2014) used the application fuzzy AHP in a wastewater treatment problem. Ghadimi et al. (2012) implemented a fuzzy rule-base combined with fuzzy AHP to assess the sustainability index of a simple manufacturing product in an automotive industry. Applying a fuzzy rule-base technique can result in generation of an excessive number of rules which can be polemic and results in tediousness and laboriousness of the technique. Khan et al. (2001) developed Green Pro in the scope of pollution prevention (P2) as a design methodology for cleaner and greener process design. The methodology involved in multi-objective optimization integrated with multi-criteria decision-making (MCDM). However, the application of the method is highly limited to large data acquisition and extensive computation load. In addition, the study focuses only on environmental and economic sustainability aspects over cradle to gate boundary. Later, Green Pro-I was proposed in an effort to overcome the earlier limitations, by incorporating AHP and fuzzy sets theory (Khan et al., 2002). A fuzzy MCDM technique was also used to enhance the decision-making analysis. Both Green Pro and Green Pro-I offered the integration of traditional LCA and MCDM methods. Following their work, Khan et al. (2004) introduced Life-cycle IndeX (LInX), an indexing system to facilitate the process design evaluation. LInX was the proposed alternative to Green Pro-I that could be cumbersome in some cases. However, the method is based on the cradle to gate boundary, where does not encompass the use and end-of-life phases.

5.4 Preliminaries

5.4.1 Sustainability hierarchy

Sustainability represents the simultaneously interaction of environment, economy, and social aspects (Dunn et al., 1995). At the same time, each of these aspects involves several criteria. To better analyze a product in terms of sustainability, the problem might be broken down into elements and sub elements in a hierarchical format. The highest level in the hierarchy indicates the global sustainability assessment. The lowest level represents the influencing factors which refer to sub elements that affect sustainability of the product. The intermediate elements between highest and lowest levels correspond to guiding criteria. Guiding criteria reflect the successive categorization of environmental, economic, and social aspects (Table 4-2). The proper selection of indictors (guiding criteria and influencing factors) should be based on a deep understanding of the problem. In fact, in the literature, plenty of studies solely focused on identifying the appropriate indicators in sustainability problems (Ahi and Searcy, 2015; Hallstedt, 2016; Henri and Journeault, 2008; Knight and Jenkins, 2009; Matthews et al., 2007; Mendoza and Prabhu, 2004; Roca and Searcy, 2012; Shiau and Liu, 2013).

Since the life-cycle of a product covers different phases, to provide the full detailed list of the sustainability indicators is time-consuming and laborious. The indicators shown in Table 5-2 represent general elements that should be considered to evaluate a product in terms of sustainability. These indicators are mostly focused on manufacturing and end-of-life phases. Therefore, in authors' point of view, the establishment of the hierarchical structure for the problem is an essential key factor in order to have a reliable sustainability index for the product. Starting from the lowest level in the hierarchy (*level 0*), the influencing factors: oil/coolant waste (OCW), chemical adhesive waste (CAW), amount of water discharged (WDIS) were determined and grouped into liquid waste index (LWI) as a primary criterion (*level 1*). Similarly, the primary criterion solid waste (SWI) is calculated according to its corresponding influencing factors which are: metal waste (MW), plastic waste (PLW), and paper waste (PAW). At *level 1*, SWI and LWI were regrouped into soil pollution (SPI) as the secondary criterion (*level 2*).

Table 5-2 Directory for guiding criteria and influencing factors

Level 4: Global assessment	**Level 3:** Tertiary criteria	**Level 2:** Secondary criteria	**Level 1:** Primary criteria	**Level 0:** Influencing factors
Overall sustainability index (OSUS)	Environmental sustainability index (ENVS)	Soil pollution index (SPI)	Solid waste index (SWI)	-Metal waste (MW) -Plastic waste (PLW) -Paper waste (PAW)
			Liquid waste index (LWI)	-Oil / coolant waste (OCW) -Chemical adhesives waste (CAW) -Amount of water discharged (WDIS)
		Air pollution index (API)	Greenhouse gasses Index (GHGI)	-Chlorofluorocarbons (CFC) -Carbon dioxide (CO2) -Methane (CH4)
			Acidification/ Eutrophication index (AEI)	-Ammonia (NH3) -mono-nitrogen oxides (NOx)
		Water consumption index (WCI)		-Amount of surface water (SURW) -Amount of ground water (GROW)
		Energy consumption index (ECI)		-Fossil energy (FOSE) -Alternative (from nature) energy (ALTE)
		Resource consumption index (RCI)		-Renewable materials/fluids (RMF) -Non-renewable materials/fluids (NMF) -Recycled materials/fluids (ReMF) -Hazardous material/fluids (HMF) -Heavy minerals (HM)
	Economic sustainability (ECOS)	Total costs index (TCI)	Direct cost index (DCI)	-Operating cost (OC) -Energy cost (EC) -Raw material cost (RC) -Packaging cost (PC) -Water cost (WC) -Transportation cost (TC)
			Indirect cost index (ICI)	-Safety equipment cost (SC) -Solid waste disposal cost (SDC) -Fluids disposal cost (FDC) -Water to discharge cost (WDC)
		Technology index (TI)		-Technology obsolescence (TO) -Equipment for technology verification (ETV) -Human resources for technology verification (HRT) -Number of operator-based technologies (NOT)
		Process index (PI)		-Processes obsolescence (PO) -Equipment for process control (EPC) -Human resources for process control (HRP) -Number of processes (NP)
		Recoverability index (RI)	Recyclable materials index (RMI)	-Recyclable metal value (MV) -Recyclable plastic value (PLV) -Recyclable paper value (PAV) -Recyclable fluids value (FV)
			Design structure index (DSI)	-Modularity level of the product (MLP) -Level of disassembly required for material separation (LDR)
			End-of-life index (ELI)	-Reusability of the product (ERU) -Re-manufacturability of the product (ERM)
	Social sustainability (SOCS)	Occupational health index (OHI)		-Exposure to Mercury (Hg) vapor (µg/m3) -Exposure to Sulphur Dioxide (SO2) gases (ppb) -Airborne particles concentration (µg/m3) (PM10) -Airborne particles concentration (µg/m3) (PM2.5) -Volatile Organic Compound (VOC) -Amount of stressing activities per process (ASA)
		Workplace environment index (WEI)		-Level of potential noise nuisance (db) (LNN) -Level of potential odor nuisance (LON)
		Safety risk index (SRI)		-Level of potential injuries for the workers (LPI)

The same procedure was repeated for other influencing factors. At *level 3*, soil pollution (SPI), air pollution (API), water consumption (WCI), energy consumption (ECI), and resource consumption (RCI) were regrouped to form environmental sustainability index (ENVS) as the tertiary criterion. Finally, the overall sustainability index (OSUS) of the product (*level 4*) regrouped the three major elements ENVS, economic sustainability index (ECOS), and social sustainability index (SOCS).

5.4.2 Theory of fuzzy sets

According to the Literature review (in Section 5.2), sustainability problems often involve high degree of uncertainty and subjectivity derived from human judgment. For this reason, the theory of fuzzy sets (Zadeh, 1965) has been proven to be a useful mathematical tool to handle vagueness and uncertainty based on the assumption that the main factors in human judgment and thought are not numbers, but linguistic terms or labels of fuzzy sets. Zadeh (1975) brought into forward the concept of linguistic values and their applications.

Linguistic values are then converted into fuzzy sets; so quantitative evaluations can be achieved. Chen and Hwang (1992) used eight different scales in order to convert linguistic terms into fuzzy sets. Their work reflected the fact that the number of verbal terms and the fuzzy scales are intuitive. The same linguistic terms may possess different meaning in different occasions.

Fuzzy set is the extension of classical set. In a classical set known also as binary or crisp set, an element belongs or not to a set: a True-False concept. Therefore, crisp numbered data are not sufficient to assess sustainability where different multidisciplinary indicators are interacting (Chen et al., 2015; Ghadimi et al., 2012; Rabbani et al., 2014). In a fuzzy set, all the elements or objects potentially belong to the set but with different grades of membership. Readers may refer to Zimmermann (1996) for a thorough treatise on the subject.

Definition 1. (*Fuzzy set*). Let $X = \{x_1, x_2, \ldots, x_n\}$ be the universe of discourse. A fuzzy set *M* of *X* is a set of order pairs $\{(x_1, \mu_{\widetilde{M}}(x_1)), (x_1, \mu_{\widetilde{M}}(x_1)), \ldots, (x_n, \mu_{\widetilde{M}}(x_n))\}$; where $\mu_{\widetilde{M}}: X \to [0,1]$ is the membership function of *M*, and $\mu_{\widetilde{M}}(x_i)$ is the membership degree of $x_i (i = 1,2, \ldots, n)$ in fuzzy set *M*. Fuzzy set *M* can be given as in Eq. (5-1).

$$M = \{(x, \mu_{\widetilde{M}}(x)) \; \forall\, x \in X \,, \mu_{\widetilde{M}}(x) \in [0, 1]\} \tag{5-1}$$

Definition 2. (*Fuzzy number*). A tilde '˜' will be placed above a symbol if it represents a fuzzy number. Triangular fuzzy numbers (TFN) are more practical due to the easiness in calculation and simpleness of features (Ko, 2013; Liu et al., 2013). Let $\tilde{A}$ be a TFN characterized as a triplet (a_1, a_2, a_3). a_1, a_2, and a_3 are denoted as the smallest possible value, the most promising value, and the highest possible value, respectively $(a_1 < a_2 < a_3)$. Each TFN has linear representations on its left and right side (Figure 5-1); therefore, its function can be defined as in Eq. (5-2). $\mu_{\tilde{A}}(x)$ is the membership function for the TFN $\tilde{A}$.

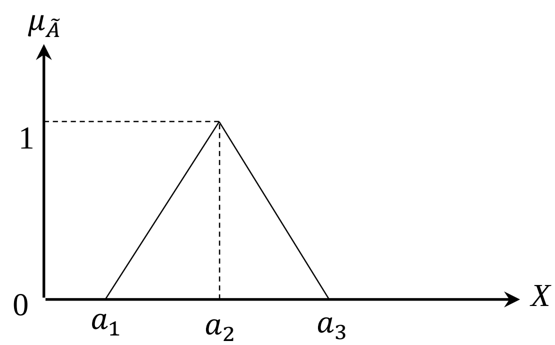

Figure 5-1 Triangular fuzzy number $\boldsymbol{\tilde{A}}$

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < a_1; \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \le x \le a_2; \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \le x \le a_3; \\ 0, & x > a_3. \end{cases} \tag{5-2}$$

Definition 3. (*Fuzzy operations*). Let $\tilde{A} = (a_1, a_2, a_3), \tilde{B} = (b_1, b_2, b_3)$ and $r \ge 0$; then, some arithmetic operations are given as follows:

$$\tilde{A} \oplus \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \tag{5-3}$$

$$\tilde{A} \ominus \tilde{B} = (a_1 - b_1, a_2 - b_2, a_3 - b_3) \tag{5-4}$$

$$\tilde{A} \otimes \tilde{B} \cong \ (a_1 * b_1, a_2 * b_2, a_3 * b_3) \tag{5-5}$$

$$r\tilde{B} \cong \ (rb_1, rb_2, rb_3) \tag{5-6}$$

$$\tilde{A} \oslash \tilde{B} \cong \ (a_1 \div b_3, a_2 \div b_2, a_3 \div b_1) \tag{5-7}$$

$$\tilde{A}^{-1} = \ (a_1, a_2, a_3)^{-1} \cong (\frac{1}{a_3}, \frac{1}{a_2}, \frac{1}{a_1}) \tag{5-8}$$

5.5 Sustainability assessment using fuzzy-inference technique (SAFT)

5.5.1 Weight assignment

In SAFT methodology we consider the fact that different decision-makers or policy-makers in the company may have different ideas and belief about the relative importance of each element in the hierarchy on the overall sustainability of the product. Relative weight indicates how many times one criterion is more dominant in compare with another criterion. This process of weight allocation is qualitative by nature because it is extracted from the opinions of the experts and consequently involves uncertain and fuzzy judgements. Therefore, Fuzzy AHP (FAHP) is used to assess the relative importance weights of the guiding criteria and influencing factors in the sustainability hierarchy. Similar to AHP, FAHP is based on the pairwise comparisons of the elements in the hierarchy model. Van Laarhoven and Pedrycz (1983) proposed the first studies applying fuzzy sets theory into AHP; where TFN was applied to express the expert's evaluation. Some modifications have been done to this technique afterwards (Boender et al., 1989; Buckley, 1985).

In the literature, Chang (1996)'s method for FAHP is the most commonly used technique (Ghadimi et al., 2012; Gharehgozli et al., 2008; Kahraman et al., 2004; Rostamzadeh and Sofian, 2011; Wang et al., 2012). Thus, in this study, in order to determine the relative weights of the elements in the sustainability hierarchy, FAHP based on Chang (1996)'s method was employed (APPENDIX 5A). To quantify the "extent" for pairwise comparison between the elements, Table 5-3 represents the linguistic terms accompanied by their TFNs.

Table 5-3 TFNs to quantify the "extent" for pairwise comparisons

Linguistic value	TFN	Reciprocal value	Reciprocal TFN
Just equal (je)	(1, 1, 1)	Just equal (je)	(1, 1, 1)
Equally more important (eqm)	(2/3, 1, 3/2)	Equally less important (eql)	(2/3, 1, 3/2)
Slightly more important (slm)	(1, 3/2, 2)	Slightly less important (sll)	(1/2, 2/3, 1)
Moderately more important (mom)	(3/2, 2, 5/2)	Moderately less important (mol)	(2/5, 1/2, 2/3)
Strongly more important (stm)	(2, 5/2, 3)	Strongly less important (stl)	(1/3, 2/5, 1/2)
Absolutely more important (abm)	(5/2, 3, 7/2)	Absolutely less important (abl)	(2/7, 1/3, 2/5)

Step 1: Start from *level 0* in the hierarchy. For each group of elements, collect the linguistic pairwise comparison-matrices. These pairwise comparison-matrices are collected from the multiple experts. Let E_k $(k = 1,2, \dots, m)$ be the experts, and C_i $(i = 1,2, \dots, n)$ be the n elements in the class. Consequently, the comparison-matrix for each expert (E_k) is obtained as Table 5-4.

Table 5-4 Comparison-matrix by expert E_k for n given elements

Expert E_k	C_1	C_2	…	C_n
C_1	*je*			
C_2		*je*		
…			*je*	
C_n				*je*

Step 2: Convert the linguistic data in the matrices to their corresponding fuzzy numbers according to Table 5-3.

Step 3: Apply FAHP to each comparison-matrix in step (2). Let w_{ik} be the weight value of C_i obtained from expert E_k; where $0 \leq w_{ik} \leq 1$ and $\sum_{i=1}^{n} w_{ik} = 1$. Therefore, m number of weight values will be available for each element C_i (Table 5-4).

Obviously the weights obtained from one expert might be different from another. This is due to the fact that each of the experts has his own viewpoints and beliefs which we would like not to ignore.

Therefore, there is a need to find a consensus among the different judgements. Using a simple average, although is simple and fast, it may not mirror the reality. Thus, it is wise to try a more precise technique to deal with this diversity of thoughts and with the aim to find an ideal solution.

In SAFT methodology, Shannon's Entropy formula has been embedded with FAHP. Entropy is the measure of "disorder" in a set of collected data. The concept of entropy has a significant role in information theory, and sometimes is referred as measure of uncertainty (Ghorbani et al., 2012; Shannon, 2001). Thus, the integration of Shannon's Entropy formula with FAHP offers a more accurate weight allowance for guiding criteria and the influencing factors.

Step 4: Calculate the uncertainty degree of the experts. Let φ_k be the uncertainty degree of expert E_k for pairwise comparison of the *n* given elements (Table 5-5). φ_k is calculated by Eq. (5-9).

$$\varphi_k = \frac{\delta_k}{\sum_{k=1}^{m} \delta_k} \tag{5-9}$$

where,

$\delta_k = 1 + \varepsilon_k$

and,

$$\varepsilon_k = \frac{1}{\ln(n)} \sum_{i=1}^{n} w_{ik} \ln(w_{ik})$$

Where, δ_k and ε_k are respectively the diversification degree and entropy of expert E_j for pairwise comparison of the *n* elements.

Step 5: Based on uncertainty degree obtained for each expert, aggregate the weight values to find the final weight (W_i) of element C_i using Eq. (5-10) (Table 5-5).

$$W_i = \sum_{k=1}^{m} \varphi_k w_{ik} \tag{5-10}$$

Table 5-5 Table of weights for the *n* given elements

Elements	E_1	E_2	E_k	E_m	Final weight
C_1	w_{11}	w_{12}	w_{1k}	w_{1m}	$W_1 = \sum_{k=1}^{m} \varphi_k w_{1k}$
C_2	w_{21}	w_{22}	w_{2k}	w_{2m}	$W_2 = \sum_{k=1}^{m} \varphi_k w_{2k}$
$\boldsymbol{C_i}$	$\boldsymbol{w_{i1}}$	$\boldsymbol{w_{i2}}$	$\boldsymbol{w_{ik}}$	$\boldsymbol{w_{im}}$	$\boldsymbol{W_i = \sum_{k=1}^{m} \varphi_k w_{ik}}$
C_n	w_{n1}	w_{n2}	w_{nk}	w_{nm}	$W_n = \sum_{k=1}^{m} \varphi_k w_{nk}$
Sum	1	1	1	1	1
Uncertainty degree	φ_1	φ_2	φ_k	φ_m	

Step 6: Repeat steps (1) to (5) for each class of elements until the final weights for all the elements in the hierarchy are obtained.

5.5.2 Index evaluation

The sustainability of the product should be evaluated based on the influencing factors (*level 0*). For some influencing factors a quantitative measurement is not applicable (i.e. level of noise, level of odor, etc.); therefore, approximate measures or quantities can be used (Doukas et al., 2010; Entzinger and Suzuki, 2010; Min et al., 2011). In this study, approximate measures were associated with numerical scales (Table 5-6) to evaluate the qualitative influencing factors.

Table 5-6 Different scales for qualitative evaluation of influencing factors

Approximate measure	Numerical scale
Very Low	[0, 2)
Low	[2, 4)
Medium	[4, 6)
High	[6, 8)
Very High	[8, 10]

Step 7: (*Data collection*). Let X_i be the universe of discourse for the influencing factor *i*; where, x_i^- and x_i^+ are defined as the extreme values. For example, in terms of qualitative factors (Table 5-6), the minimum and maximum possible values (x_i^- and x_i^+) are 0 and 10, respectively.

The extreme values can be established according to regulations and standards, or in some cases it can be defined based on logic thoughts. For instance, the total cost for a product cannot be greater than its selling price. So, $x_i \in [x_i^-, x_i^+]$ is defined as the input data for the influencing factor *i*. Influencing factors may have negative or positive character. For example cost has a negative character (the lower, the better); while, recyclability has a positive character (the higher, the better).

Step 8: (*Effectiveness assessment*). Let I_i be the index representing the effect of influencing factor *i* on product sustainability. The higher I_i is, the better influencing factor *i* performs in terms of sustainability. In this study, five triangular fuzzy sets have been considered for effectiveness assessment (I_i) of the positive and negative influencing factors. For each fuzzy set a score was assigned (Figure 5-2 and Table 5-7). Accordingly, I_i is a value in the range of [0, 1] and calculated using Eq. (5-11).

$$I_i = \frac{0.2\mu_{\widetilde{LE}}(x_i) + 0.4\mu_{\widetilde{SE}}(x_i) + 0.6\mu_{\widetilde{ME}}(x_i) + 0.8\mu_{\tilde{E}}(x_i) + 1.0\mu_{\widetilde{GE}}(x_i)}{\mu_{\widetilde{LE}}(x_i) + \mu_{\widetilde{SE}}(x_i) + \mu_{\widetilde{ME}}(x_i) + \mu_{\tilde{E}}(x_i) + \mu_{\widetilde{GE}}(x_i)} \tag{5-11}$$

5.5.3 Aggregation

In previous sub sections, we learned how to obtain the relative weights for the elements in the sustainability hierarchy. We also explained the fuzzy technique for effectiveness assessment of the influencing factors. Once the indices for the influencing factors in *level 0* are obtained, the indices for the guiding criteria in successive levels can be calculated through a stepwise aggregation process.

Step 9: Let C_j be an element at *level 1* in the hierarchy which groups *n* sub elements C_i ($i = 1,2,\dots,n$) at *level 0*. If W_i and I_i are respectively the obtained relative weight and effectiveness index for C_i, then I_j is the effectiveness index for C_j and calculated as in Eq. (5-12).

$$I_j = \sum_{i=1}^{n} W_i I_i \tag{5-12}$$

Step 10: Apply the similar aggregation described in step (9) to subsequent levels in the hierarchy until the overall sustainability index is obtained.

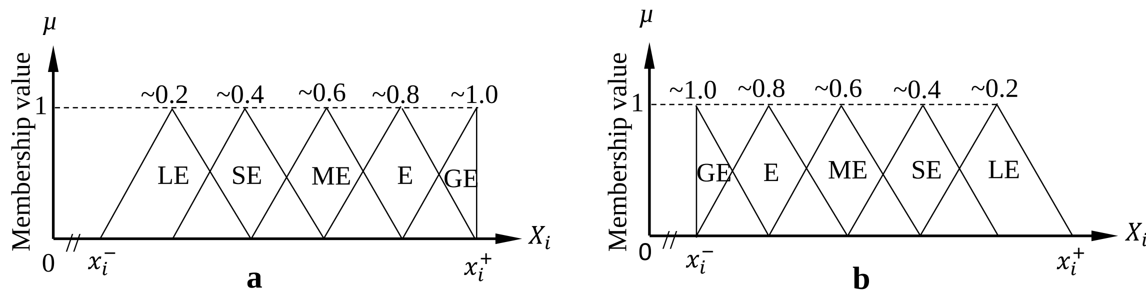

Figure 5-2 Graphic representation of fuzzy sets: (a) for positive influencing factors; (b) for negative influencing factors

Table 5-7 Fuzzy sets for effectiveness assessment of influencing factors

Linguistic value	TFN (**Positive** influencing factor)	TFN (**Negative** influencing factor)	Score
Least Effective (LE)	$\left(x_i^-, \frac{x_i^+ + 4x_i^-}{5}, \frac{2x_i^+ + 3x_i^-}{5}\right)$	$\left(\frac{3x_i^+ + 2x_i^-}{5}, \frac{4x_i^+ + x_i^-}{5}, x_i^+\right)$	0.2
Slightly Effective (SE)	$\left(\frac{x_i^+ + 4x_i^-}{5}, \frac{2x_i^+ + 3x_i^-}{5}, \frac{3x_i^+ + 2x_i^-}{5}\right)$	$\left(\frac{2x_i^+ + 3x_i^-}{5}, \frac{3x_i^+ + 2x_i^-}{5}, \frac{4x_i^+ + x_i^-}{5}\right)$	0.4
Moderately Effective (ME)	$\left(\frac{2x_i^+ + 3x_i^-}{5}, \frac{3x_i^+ + 2x_i^-}{5}, \frac{4x_i^+ + x_i^-}{5}\right)$	$\left(\frac{x_i^+ + 4x_i^-}{5}, \frac{2x_i^+ + 3x_i^-}{5}, \frac{3x_i^+ + 2x_i^-}{5}\right)$	0.6
Effective (E)	$\left(\frac{3x_i^+ + 2x_i^-}{5}, \frac{4x_i^+ + x_i^-}{5}, x_i^+\right)$	$\left(x_i^-, \frac{x_i^+ + 4x_i^-}{5}, \frac{2x_i^+ + 3x_i^-}{5}\right)$	0.8
Greatly Effective (GE)	$\left(\frac{4x_i^+ + x_i^-}{5}, x_i^+, x_i^+\right)$	$\left(x_i^-, x_i^-, \frac{x_i^+ + 4x_i^-}{5}\right)$	1.0

A summary of all the steps in the methodology are shown in the APPENDIX 5B.

5.5.4 Practical implementation of SAFT methodology

In this section with the aim to make clear the steps to follow to calculate the overall sustainability, a simple implementation of SAFT methodology on a product X is presented. First the hierarchical structure for the product was established (Figure 5-3). The guiding criteria and influencing factors were selected from the ones provided in Table 5-2.

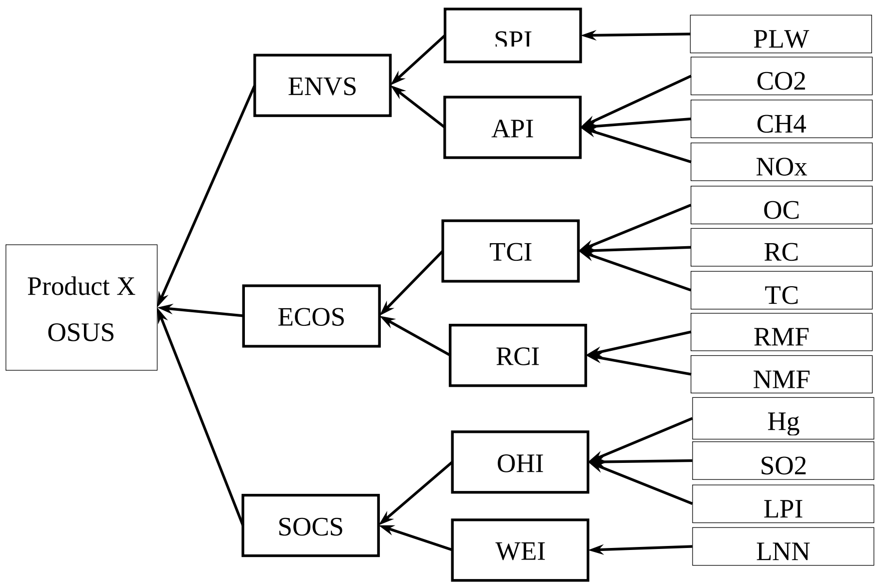

Figure 5-3 Hierarchical structure to evaluate sustainability of product X

Considering CO2, CH4, and NOx as the elements of the first group at *level 0*, in **Step 1**, the three experts made pairwise comparisons for the elements. The assigned linguistic evaluations then translated into fuzzy numbers (**Step 2**). FAHP was employed afterwards to obtain the relative weights derived from each expert (**Step 3**). Table 5-9 tabulated the results from steps (1) to (3). In **Step 4**, uncertainty degree (φ) of the experts were calculated by Eq. (5-9). Consequently in **Step 5**, the final weights of the elements were obtained using Eq. (5-10). Steps (1) to (5) were repeated for the remaining groups in the hierarchy (Table 5-9).

Table 5-8 Pairwise comparisons for elements in the first group at *level 0*

	CH4	CO2	NOx						*FAHP*
Expert 1									
CH4	*je*	*mom*	*slm*		(1, 1, 1)	(3/2, 2, 5/2)	(1, 3/2, 2)		0.55
				⇒				⇒	
CO2		*je*	*eqm*		(2/5, 1/2, 2/3)	(1, 1, 1)	(2/3, 1, 3/2)		0.20
NOx			*je*		(1/2, 2/3, 1)	(2/3, 1, 3/2)	(1, 1, 1)		0.25
Expert 2									
CH4	*je*	*slm*	*mom*		(1, 1, 1)	(1, 3/2, 2)	(3/2, 2, 5/2)		0.55
				⇒				⇒	
CO2		*je*	*mol*		(1/2, 2/3, 1)	(1, 1, 1)	(2/5, 1/2, 2/3)		0.08
NOx			*je*		(2/5, 1/2, 2/3)	(3/2, 2, 5/2)	(1, 1, 1)		0.37
Expert 3									
CH4	*je*	*eqm*	*stm*		(1, 1, 1)	(2/3, 1, 3/2)	(2, 5/2, 3)		0.54
				⇒				⇒	
CO2		*je*	*eqm*		(2/3, 1, 3/2)	(1, 1, 1)	(2/3, 1, 3/2)		0.31
NOx			*je*		(1/3, 2/5, 1/2)	(2/3, 1, 3/2)	(1, 1, 1)		0.15

The data for each influencing factor as well as the extreme values were determined (**Step 7**). Among the influencing factors, only RMF has positive character. In **Step 8** by using Table 5-7, fuzzy sets for effectiveness evaluation of influencing factors were established and then the indices were calculated by Eq. (5-11) (Table 5-10). Finally through a stepwise aggregation, the indices for the sustainability elements in the successive levels were calculated (**Step 9** and **Step 10**). The overall indices of the current design for product X are tabulated in Table 5-11.

Table 5-9 Table of weights for the groups of elements in the hierarchy

	Expert 1	Expert 2	Expert 3	Final weight		Expert 1	Expert 2	Expert 3	Final weight
1st group at level 0					*1st group at level 1*				
CH_4	0.55	0.55	0.54	0.54	SPI	0.65	0.17	0.67	0.32
CO_2	0.20	0.08	0.31	0.17	API	0.35	0.83	0.33	0.68
NO_x	0.25	0.37	0.15	0.29	φ	0.13	0.69	0.17	
φ	0.24	0.48	0.28		*2nd group at level 1*				
2nd group at level 0					TCI	0.75	0.86	0.33	0.76
OC	0.25	0.71	0.24	0.51	RCI	0.25	0.14	0.67	0.24
RC	0.59	0.21	0.55	0.37	φ	0.27	0.60	0.12	
TC	0.16	0.08	0.21	0.12	*3rd group at level 1*				
φ	0.26	0.57	0.17		OHI	0.33	0.25	0.17	0.22
3rd group at level 0					WEI	0.67	0.75	0.83	0.78
RMF	0.50	0.67	0.75	0.73	φ	0.14	0.31	0.56	
NMF	0.50	0.33	0.25	0.27	*1st group at level 2*				
φ	0.00	0.31	0.69		ENVS	0.16	0.66	0.53	0.51
4th group at level 0					ECOS	0.54	0.08	0.14	0.20
Hg	0.12	0.18	0.10	0.14	SOCS	0.30	0.26	0.33	0.29
SO_2	0.32	0.74	0.65	0.63	φ	0.22	0.54	0.24	
LPI	0.56	0.08	0.25	0.23					
φ	0.20	0.48	0.32						

Table 5-10 Fuzzy effective assessment of the influencing factors

i	Factor i	Unit	Input (x_i)	Fuzzy evaluation sets					$\mu(x_i)$	Index (I_i)
				LE	SE	ME	E	GE		
1	PLW	kg/product	0.011	(0.033, 0.044, 0.055)	(0.022, 0.033, 0.044)	(0.011, 0.022, 0.033)	(0, 0.011, 0.022)	(0, 0, 0.011)	$\mu_{\tilde{E}} = 1$	0.800
2	CO2	g/product	1390	(1084, 1446, 1807)	(723, 1084, 1446)	(361, 723, 1084)	(0, 361, 723)	(0, 0, 361)	$\mu_{\widetilde{LE}} = 0.846$ $\mu_{\widetilde{SE}} = 0.154$	0.231
3	CH4	g/product	8.150	(6.36, 8.48, 10.6)	(4.24, 6.36, 8.48)	(2.12, 4.24, 6.36)	(0, 2.12, 4.24)	(0, 0, 2.12)	$\mu_{\widetilde{LE}} = 0.844$ $\mu_{\widetilde{SE}} = 0.156$	0.231
4	NOx	g/product	3.250	(3, 4, 5)	(2, 3, 4)	(1, 2, 3)	(0, 1, 2)	(0, 0, 1)	$\mu_{\widetilde{LE}} = 0.25$ $\mu_{\widetilde{SE}} = 0.75$	0.350
5	OC	\$/product	2.373	(10.47, 13.96, 17.45)	(6.98, 10.47, 13.96)	(3.49, 6.98, 10.47)	(0, 3.49, 6.98)	(0, 0, 3.49)	$\mu_{\tilde{E}} = 0.68$ $\mu_{\widetilde{GE}} = 0.32$	0.864
6	RC	\$/product	2.07	(3.078, 4.104, 5.13)	(2.052, 3.078, 4.104)	(1.026, 2.052, 3.078)	(0, 1.026, 2.052)	(0, 0, 1.026)	$\mu_{\widetilde{SE}} = 0.018$ $\mu_{\widetilde{ME}} = 0.982$	0.596
7	TC	\$/product	1.12	(1.452, 1.936, 2.42)	(0.968, 1.452, 1.936)	(0.484, 0.968, 1.452)	(0, 0.484, 0.968)	(0, 0, 0.484)	$\mu_{\widetilde{SE}} = 0.314$ $\mu_{\widetilde{ME}} = 0.686$	0.537
8	RMF	g/product	0.253	(0, 0.147, 0.295)	(0.147, 0.295, 0.442)	(0.295, 0.442, 0.59)	(0.442, 0.59, 0.74)	(0.59, 0.74, 0.74)	$\mu_{\widetilde{LE}} = 0.284$ $\mu_{\widetilde{SE}} = 0.716$	0.343
9	NMF	g/product	0.484	(0.442, 0.59, 0.74)	(0.295, 0.442, 0.59)	(0.147, 0.295, 0.442)	(0, 0.147, 0.295)	(0, 0, 147)	$\mu_{\widetilde{LE}} = 0.284$ $\mu_{\widetilde{SE}} = 0.716$	0.343
10	Hg	g/product	35e-6	(38e-6, 5e-6, 63e-6)	(25e-6, 38e-6, 5e-6)	(13e-6, 25e-6, 38e-6)	(0, 13e-6, 25e-6)	(0, 0, 13e-6)	$\mu_{\widetilde{SE}} = 0.778$ $\mu_{\widetilde{ME}} = 0.222$	0.444
11	SO2	g/product	1.95	(2.4, 3.2, 4)	(1.6, 2.4, 3.2)	(0.8, 1.6, 2.4)	(0, 0.8, 1.6)	(0, 0, 08)	$\mu_{\widetilde{SE}} = 0.438$ $\mu_{\widetilde{ME}} = 0.563$	0.513
12	LPI	number/year	17	(14.4, 19.2, 24)	(9.6, 14.4, 19.2)	(4.8, 9.6, 14.4)	(0, 4.8, 9.6)	(0, 0, 4.8)	$\mu_{\widetilde{LE}} = 0.542$ $\mu_{\widetilde{SE}} = 0.458$	0.292
13	LNN	dimensionless	3	(6, 8, 10)	(4, 6, 8)	(2, 4, 6)	(0, 2, 4)	(0, 0, 2)	$\mu_{\widetilde{ME}} = 0.5$ $\mu_{\tilde{E}} = 0.5$	0.700

Table 5-11 Overall indices of current design for product X

Level 0	Index	Weight	*Level 1*	Index	Weight	*Level 2*	Index	Weight	*Level 3*	Index
PLW	0.800	1.00	SPI	0.800	0.32	ENVS	0.437	0.51	OSUS	0.552
CO2	0.231	0.17	API	0.266	0.68					
CH4	0.231	0.54								
NOx	0.35	0.29								
OC	0.864	0.51	TCI	0.726	0.76	ECOS	0.634	0.20		
RC	0.596	0.37								
TC	0.537	0.12								
RMF	0.343	0.73	RCI	0.343	0.24					
NMF	0.343	0.27								
Hg	0.444	1.00	OHI	0.699	0.22	SOCS	0.700	0.29		
SO2	0.513	0.14								
LPI	0.292	0.63								
LNN	0.700	1.00	WEI	0.700	0.78					

5.6 Results and discussion

5.6.1 Fuzzy rule-base system versus SAFT: Strengths and weaknesses

In order to assess sustainability of products/processes, some researchers proposed the application of fuzzy rule-base system. In this section the results of our proposed methodology have been compared with the results of fuzzy rule-base method (Table 5-12). To this aim we used the same data provided in the work of (Ghadimi et al., 2012) implementing the methodology explained previously. The results from the two methodologies are pretty the same which validates our proposed technique.

In fuzzy rule-base, in order to have a precise evaluation, the whole experts' knowledge should be carefully translated into some sets of "IF-THEN" rules using different operators such as AND, OR, and NOT. In some cases, choosing an appropriate fuzzy operator is not evident. Besides, the number of rules can extensively grows by increasing the number of input variables and membership functions related to them. Therefore, constructing a rules database to have a definite assessment can be very laborious and time-consuming.

Table 5-12 Comparison of results obtained by SAFT and fuzzy rule-base methodologies

	SAFT methodology	Fuzzy rule-base (Ghadimi et al., 2012)
Environment index	0.44	0.44
Economy index	0.56	0.54
Social index	0.55	0.55
Overall sustainability index	0.50	0.51

Ghadimi et al. (2012) established a list of influencing factors and guiding criteria for sustainability assessment of a simple automotive part. Then, for each group of influencing factors, they applied a fuzzy rule-base system in order to generate an index for the guiding criterion in the next level. The accuracy of the index obtained for guiding criteria is directly influenced by the rules generated, and once the number of rules increases this process of knowledge extraction would be more complicated and misleading. For example, influencing factors: *CO2*, *CH4*, and *NO2* were grouped under guiding criterion *greenhouse effect*; and for each influencing factor three *low*, *medium*, *high* membership functions were determined. As a result, to assess the index of *greenhouse effect*, using AND operator, 3^3 rules were constructed based on knowledge extraction from the group of experts.

Looking deep into the rules, one can notice that the philosophy behind the creation of each rule is somehow originated from the relative importance of the input variables. For instance having the rules "*If (CO2 emission is <u>high</u>) and (CH4 emission is <u>low</u>) and (NO2 emission is <u>low</u>) then (greenhouse index is **BAD**)*" and "*If (CO2 emission is <u>low</u>) and (CH4 emission is low) and (NO2 emission is <u>high</u>) then (greenhouse index is **GOOD**)*" represents the fact that the influence of CO2 is more dominant than NO2 in the expert's point of view. Consequently, related to *greenhouse effect* only, 27 rules are generated which can lead to redundancy and inexactitude.

In contrast with fuzzy rule-base inference systems, SAFT methodology offers an easier and more practical platform to evaluate sustainability of products/processes since there is no need to generate rules. In addition, the knowledge extraction from the experts is done individually which avoids one expert influences on the other's opinion. Thus, the final consensus is found via calculating the level of uncertainty among them. Even though the methodology provides these advantages, in this study, only linear fit functions (triangular fuzzy sets) were used due to simplicity in the calculations. Different non-linear membership functions such as sigmoid, gaussian, and pi associated with fuzzy hedges (Jin and Bose, 2002) could be applied depending on the case study in order to overcome this potential weakness. Also, in terms of qualitative influencing factors, crisp scales were used to approximate the input values (Table 5-6). It would be a good idea to employ hesitant fuzzy sets (Torra, 2010) in future works.

5.6.2 SAFT user interface

A user interface has been developed to facilitate the implementation of the methodology for potential users (Figure 5-4). Two interfaces have been designed: An interface for data collection, and core interface for processing these data. Based on the established hierarchical structure, tables in the format of survey will be sent to the experts individually to do the pairwise comparisons. The feedback from the experts as well as the input data for the influencing factors are analyzed in the core interface. The output of the tool will be the indices for all the elements in the hierarchy. Comparative graphs can be generated to identify the weak points in the current design and recommend improvements for new design. The current user interface was developed in Microsoft Excel spread worksheets using visual basic programming.

5.6.3 Managerial insights

The results of this research can have important implications in life-cycle management of different products. Having an appropriate end-of-life treatment, especially for complex products, is considered as an important activity towards sustainability. This study was performed within the framework of the project (CRIAQ-ENV412) "Process for advanced management and technologies of aircraft end-of-life". The goal of the project was to ameliorate the existing managerial and technical methods in the field of aircraft end-of-life recycling. To achieve this, different disassembly/dismantling strategies might be involved (Mascle et al., 2015; Sabaghi et al., 2015b). Certainly, these potential strategies have different overall sustainability performances. Therefore, it is highly interesting for the managers and decision-makers to count with an expert tool that allows them to evaluate the best and most feasible strategies in terms of sustainability (Sabaghi et al., 2015a). Similarly, other industries such as automotive, naval, railway and so on, have also challenges regarding their products' design, assembly, supplier selection, disassembly, maintenance, etc. (Hallstedt, 2016; Sabaghi et al., 2016; Vargas Hernandez et al., 2012). Accordingly, they need to identify the appropriate elements in the sustainability hierarchy. The use of SAFT methodology is a very promising approach to solve these kind of problems in the direction of green(er) products/processes.

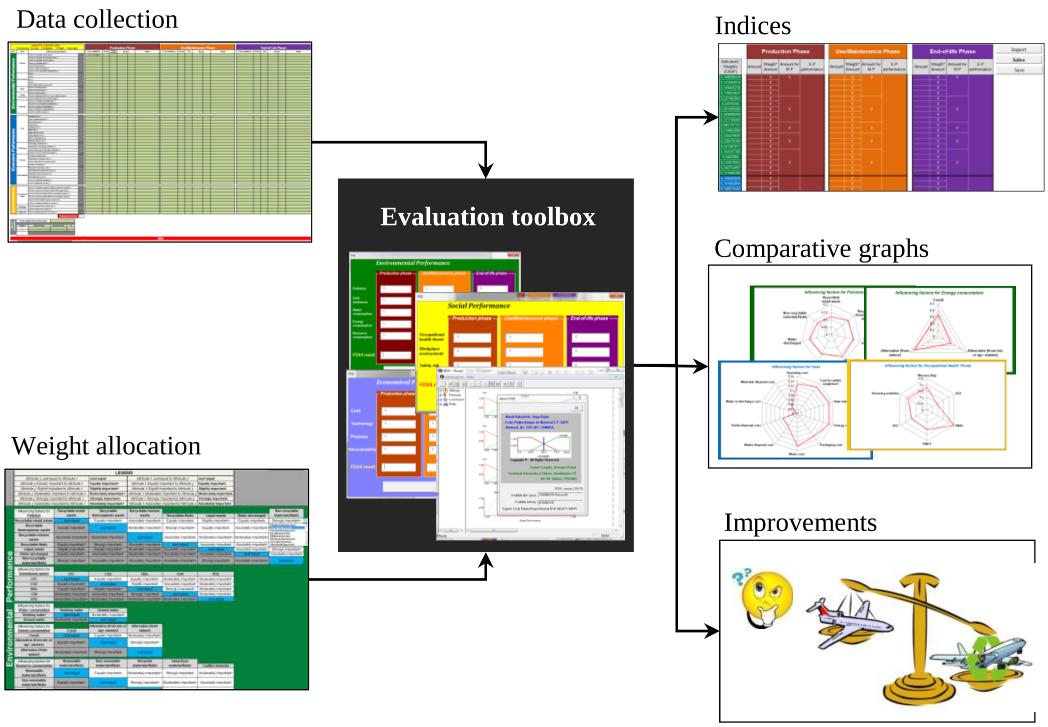

Figure 5-4 Structure of SAFT user interface

5.7 Conclusion and further studies

Manufacturers of new generation products are not only thinking of embedding new functions to their products but also a better sustainability performance over the life-cycle. Counting with mathematical tools that enables to quantify sustainability of products/processes will allow to monitor sustainability in all phases of life-cycle and bring value-added. In this study, having provided a comprehensive review of the literature, we introduced a methodology to easily and practically assess the sustainability performance of a target product. First, the hierarchical structure of the product is established containing all the influencing factors and guiding criteria that will be considered. Then, the relative importance of each element in the hierarchy are determined using FAHP and analyzing the levels of experts' uncertainty with Shannon's entropy formula. Afterwards, an index is assigned to represent effectiveness of each influencing factor. A fuzzy-inference system is applied to handle the uncertainties and vagueness existent in the nature of the influencing factors. Finally through a stepwise aggregation, the indices of the elements in subsequent levels of the hierarchy are obtained.

The proposed methodology was validated and compared with fuzzy rule-base technique. The results obtained by SAFT were very close to the ones obtained by fuzzy rule-base method. This comparison allowed to conclude that SAFT is more practical and easier method since it is independent of having fuzzy rules. Generating rules in fuzzy rule-base can leads to redundancy and inaccuracy.

The current methodology was developed based on triangular fuzzy sets. Further studies should be focused on using non-linear membership functions which might be more suitable depending on the case study. Also, hesitant or intuitionistic fuzzy numbers can be employed to measure the qualitative influencing factors to better dealing with uncertainty and fuzziness. More advanced programming languages can be used in order to broaden the application of the tool in more complex sustainability problems. The tool should be applied to different case studies to validate its strength and applicability.

5.8 ACKNOWLEDGEMENTS

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5.9 APPENDIX 5A

Chang (1996) proposed the extent analysis method which is used as the most common method in the solution of FAHP applications. In the method, fuzzy number is used to quantify the "extent".

For the extent analysis of each object, a fuzzy synthetic degree value can be obtained based on the fuzzy values. $X = \{x_1, x_2, \dots, x_n\}$ can present elements of the alternatives as an object set. Besides that, the elements of the criteria as a goal set are represented by $U = \{u_1, u_2, \dots, u_m\}$. According to the method of Chang's (1996) extent analysis, each object is taken and extent analysis for each goal, g_i, is performed respectively. Consequently, *m* extent analysis values for each object can be obtained (Eq. (5A-1)).

$$M_{g_1}^{1}, M_{g_2}^{2}, \dots \dots, M_{g_i}^{j}, \dots \dots, M_{g_n}^{m}; \quad i = 1, 2, \dots, n\,;\ j = 1, 2, \dots, m \tag{5A-1}$$

Where, $M_{g_i}^{j}$ are fuzzy numbers. Accordingly, the steps of Chang's extent analysis are described as follows:

Step 1- Fuzzy synthetic extent calculation (Eq. (5A-2)).

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} \tag{5A-2}$$

Let's define $M_{g_i}^{j} = (a_{ij}, b_{ij}, c_{ij})$ as triangular fuzzy numbers. So, $\sum_{j=1}^{m} M_{g_i}^{j}$ is obtained by having fuzzy addition operation of *m* extent analysis values for a particular matrix (Eq. (5A-3)).

$$\begin{aligned}\sum_{j=1}^{m} M_{g_i}^{j} &= (a_{i1}, b_{i1}, c_{i1}) \oplus (a_{i2}, b_{i2}, c_{i2}) \oplus \dots \oplus (a_{im}, b_{im}, c_{im}) \\ &= \left(\sum_{j=1}^{m} a_{ij}, \sum_{j=1}^{m} b_{ij}, \sum_{j=1}^{m} c_{ij}\right) = (a_i', b_i', c_i')\end{aligned} \tag{5A-3}$$

Based on Eq. (5A-3), $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$ is calculated as follows:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} a_{ij}, \sum_{j=1}^{m} b_{ij}, \sum_{j=1}^{m} c_{ij}\right) = \left(\sum_{i=1}^{n} a'_i, \sum_{i=1}^{n} b'_i, \sum_{i=1}^{n} c'_i\right) \tag{5A-4}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} c'_i}, \frac{1}{\sum_{i=1}^{n} b'_i}, \frac{1}{\sum_{i=1}^{n} a'_i}\right) \tag{5A-5}$$

Consequently,

$$\begin{aligned} S_i &= \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = (a'_i, b'_i, c'_i) \otimes \left(\frac{1}{\sum_{i=1}^{n} c'_i}, \frac{1}{\sum_{i=1}^{n} b'_i}, \frac{1}{\sum_{i=1}^{n} a'_i}\right) \\ &= \left(\frac{a'_i}{\sum_{i=1}^{n} c'_i}, \frac{b'_i}{\sum_{i=1}^{n} b'_i}, \frac{c'_i}{\sum_{i=1}^{n} a'_i}\right) = (a_i, b_i, c_i) \end{aligned} \tag{5A-6}$$

Step 2- Possibility degree calculation:

If $S_1 = (a_1, b_1, c_1)$ and $S_2 = (a_2, b_2, c_2)$ then $V(S_1 \geq S_2)$ indicates the possibility degree of S_1 is greater than S_2 is calculated according to Eqs. (5A-7)-(5A-9)

$$V(S_1 \geq S_2) = \underbrace{sup}_{y \geq x}\left(min\{\mu_{S_1}(x), \mu_{S_2}(y)\}\right) \tag{5A-7}$$

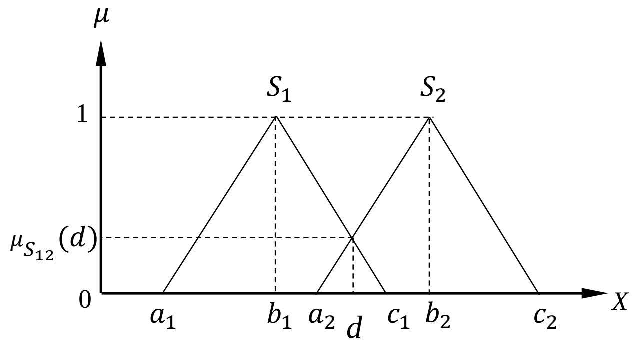
Where, $V(S_1 \geq S_2)$ can be equivalently expressed as follows:

$$V(S_1 \geq S_2) = hgt(S_1 \cap S_2) = \mu_{S_{12}}(d) \tag{5A-8}$$

Accordingly,

$$V(S_1 \geq S_2) = \mu_{S_{12}}(d) = \begin{cases} 1 & if \quad a_1 \geq a_2; \\ 0 & if \quad a_1 \leq a_2; \\ \dfrac{a_2 - c_1}{(b_1 - c_1) - (b_2 - a_2)} & if \;\; otherwise; \end{cases} \tag{5A-8}$$

Where, d is the ordinate of the highest intersection point between S_1 and S_2 (Appendix 5A-Figure 5-5)



Appendix 5A-Figure 5-5 Possibility degree $V(S_1 \geq S_2)$ between two fuzzy numbers S_1 and S_2

Therefore, the possibility degree for fuzzy number S_i to be greater than all the fuzzy numbers $S_k; k = 1, 2, \dots, n \;\; k \neq i$ is defined as $w'(A_i)$ and calculated as following:

$$\begin{aligned} V(S_i \geq S_k) &= V(S_i \geq S_1, S_2, \dots, S_{k \neq i}, \dots, S_n) \\ &= V\big((S_i \geq S_1), (S_i \geq S_2), \dots, (S_i \geq S_{k \neq i}), \dots, (S_i \geq S_n)\big) \\ &= \min\big(V(S_i \geq S_1), V(S_i \geq S_2), \dots, V(S_i \geq S_{k \neq i}), \dots, V(S_i \geq S_n)\big) \\ &= \min V(S_i \geq S_k);\; k = 1, 2, \dots, n \;\; k \neq i \end{aligned} \tag{4A-9}$$

Assuming $w'(A_i) = \min V(S_i \geq S_k);\; k = 1, 2, \dots, n \;\; k \neq i$, the weight vector (not normalized) for the alternatives is given in Eq. (5A.10).

$$W' = \big(w'(A_1), w'(A_2), \dots, w'(n)\big)^T \tag{5A-10}$$

Where, $A_i; i = 1, 2, \dots, n$ are the alternatives.

Step 3- Normalization (Eq. (5A.11))

$$W = \big(w(A_1), w(A_2), \dots, w(n)\big)^T \tag{5A-11}$$

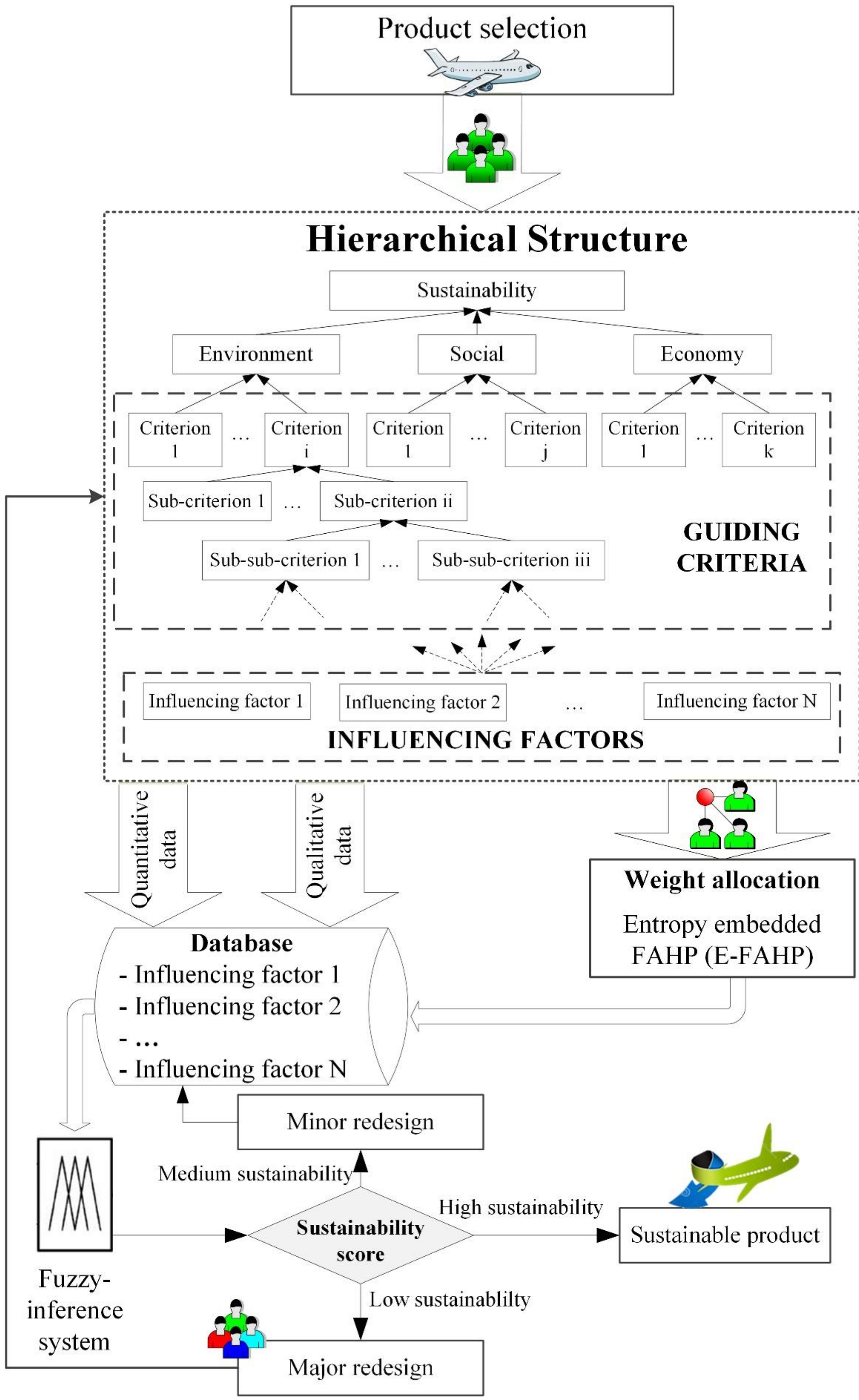
Where,

$$w(A_i) = \frac{w'(A_i)}{\sum_{i=1}^{n} w'(A_i)}$$

$w(A_i)$ is a non-fuzzy number which indicates the priority weight of alternative A_i over the other alternatives.

5.10 APPENDIX 5B

The proposed tool is based on a hybrid fuzzy assessment method. The sustainability problem is break down into its guiding criteria and influencing factors. To assess the relative importance of these criteria and influencing factors a weight should be allocated to each of them using Entropy embedded with Fuzzy Analytic hierarchy process (E-FAHP) technique. To make the index evaluation, Fuzzy-inference technique is applied to the influencing factors (input data) that are at the lowest level in the hierarchical structure. Once the final sustainability score is obtained, the design team can decide whether the product requires minor or major redesign with the goal to ameliorate the sustainability of the product (Appendix 5B-Figure 5-6)



Appendix 5B-Figure 5-6 Schematic representation of the proposed methodology for SAFT tool

5.11 REFERENCES

Ahi, P., & Searcy, C. (2015). An analysis of metrics used to measure performance in green and sustainable supply chains. *Journal of Cleaner Production*, *86*, 360–377

Allen, R., 1980. *How to save the world. Strategy for world conservation*. Kogan Page Ltd.

Andriantiatsaholiniaina, L. A., Kouikoglou, V. S., & Phillis, Y. A. (2004). Evaluating strategies for sustainable development: Fuzzy logic reasoning and sensitivity analysis. *Ecological Economics*, *48*, 149–172.

Boender, C. G. E., de Graan, J. G., & Lootsma, F. A. (1989). Multi-criteria decision analysis with fuzzy pairwise comparisons. *Fuzzy Sets and Systems*, *29*, 133–143.

Bovea, M. D., & Pérez-Belis, V. (2012). A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. *Journal of Cleaner Production*, *20*, 61–71.

Bruno, G., Esposito, E., & Genovese, A. (2015). A model for aircraft evaluation to support strategic decisions. *Expert Systems with Applications*, *42*, 5580–5590.

Buckley, J. J. (1985). Fuzzy hierarchical analysis. *Fuzzy Sets and Systems*, 17, 233–247.

Canavese, D., & Ortega, N. R. S. (2013). A proposal of a fuzzy rule-based system for the analysis of health and health environments in Brazil. *Ecological Indicators*, *34*, 7–14.

Canavese, D., Ortega, N. R. S., & Queirós, M. (2014). The assessment of local sustainability using fuzzy logic: An expert opinion system to evaluate environmental sanitation in the Algarve region, Portugal. *Ecological Indicators*, 36, 711–718.

Chang, D.-Y. (1996). Applications of the extent analysis method on fuzzy AHP. European *Journal of Operational Research*, *95*, 649–655.

Chen, D., Chu, X., Yang, X., Sun, X., Li, Y., & Su, Y. (2015). PSS solution evaluation considering sustainability under hybrid uncertain environments. *Expert Systems with Applications*, *42*, 5822–5838.

Chen, S.-J. J., & Hwang, C. L. (1992). *Fuzzy multiple attribute decision making: Methods and applications*. New York, Inc.: Springer-Verlag.

CRIAQ-ENV412, Process for advanced management and technologies of aircraft end-of-life, http://www.polymtl.ca/env412/index.php.

Curtis, H., & Walker, J. (2001). *Design Council European survey of manufacturing companies' attitudes towards design for sustainability*. Design Council.

Doukas, H., Karakosta, C., & Psarras, J. (2010). Computing with words to assess the sustainability of renewable energy options. *Expert Systems with Applications, 37,* 5491–5497.

Dunn, E. G., Keller, J. M., Marks, L. A., Ikerd, J. E., Gader, P. D., & Godsey, L. D. (1995). Extending the application of fuzzy sets to the problem of agricultural sustainability, uncertainty modeling and analysis, 1995, and annual conference of the North American fuzzy information processing society. In *Proceedings of ISUMA – NAFIPS'95, third international symposium on* (pp. 497–502).

Entzinger, J. O., & Suzuki, S. (2010). Modeling of the visual approach to landing using neural networks and fuzzy supervisory control. *Aerospace Science and Technology, 14*, 118–125.

Fan, G., Zhong, D., Yan, F., & Yue, P. (2016). A hybrid fuzzy evaluation method for curtain grouting efficiency assessment based on an AHP method extended by D numbers. *Expert Systems with Applications, 44,* 289–303.

Ghadimi, P., Azadnia, A. H., Mohd, Yusof, Mat, N., & Saman, M. Z. (2012). A weighted fuzzy approach for product sustainability assessment: A case study in automotive industry. *Journal of Cleaner Production, 33*, 10–21.

Gharehgozli, A. H., Rabbani, M., Zaerpour, N., & Razmi, J. (2008). A comprehensive decision-making structure for acceptance/rejection of incoming orders in make-to-order environments. *The International Journal of Advanced Manufacturing Technology, 39*, 1016–1032.

Ghorbani, M., Arabzad, S. M., & Bahrami, M. (2012). Implementing Shannon entropy, SWOT and mathematical programming for supplier selection and order allocation. *International Journal of Supply Chain Management, 1*, 43–47.

Hallstedt, S. I. (2016). Sustainability criteria and sustainability compliance index for decision support in product development. *Journal of Cleaner Production*. doi:10. 1016/j.jclepro.2015.06.068.

Hemdi, A. R., Saman, M. Z. M., & Sharif, S. (2013). Sustainability evaluation using fuzzy inference methods. *International Journal of Sustainable Energy, 32*, 169– 185.

Henri, J.-F., & Journeault, M. (2008). Environmental performance indicators: An empirical study of Canadian manufacturing firms. *Journal of Environmental Management, 87*, 165–176.

Hu, G., & Bidanda, B. (2009). Modeling sustainable product lifecycle decision support systems. *International Journal of Production Economics, 122*, 366–375.

Hur, T., Lee, J., Ryu, J., & Kwon, E. (2005). Simplified LCA and matrix methods in identifying the environmental aspects of a product system. *Journal of Environmental Management, 75*, 229–237.

IUCN (1980). World conservation strategy: Living resource conservation for sustainable development. Gland, Switzerland. In *International Union for the Conservation of Nature and Natural Resources (IUCN).*

Jawahir, I., Rouch, K., Dillon, O., Holloway, L., & Hall, A. (2007). Design for sustainability (DFS): New challenges in developing and implementing a curriculum for next generation design and manufacturing engineers. *International Journal of Engineering Education, 23*, 1053–1064.

Jin, Z., & Bose, B. K. (2002). Evaluation of membership functions for fuzzy logic controlled induction motor drive. In *IECON 02 [industrial electronics society], IEEE 2002 28th annual conference of the: 221* (pp. 229–234).

Kaebernick, H., Anityasari, M., & Kara, S. (2002). A technical and economic model for end-of-life (EOL) options of industrial products. *International Journal of Environment and Sustainable Development, 1*, 171–183.

Kahraman, C., Cebeci, U., & Ruan, D. (2004). Multi-attribute comparison of catering service companies using fuzzy AHP: The case of Turkey. *International Journal of Production Economics*, 87, 171–184.

Khan, F. I., Natrajan, B. R., & Revathi, P. (2001). GreenPro: A new methodology for cleaner and greener process design. *Journal of Loss Prevention in the Process Industries, 14*, 307–328.

Khan, F. I., Sadiq, R., & Husain, T. (2002). GreenPro-I: A risk-based life cycle assessment and decision-making methodology for process plant design. *Environmental Modelling & Software, 17*, 669–692.

Khan, F. I., Sadiq, R., & Veitch, B. (2004). Life cycle iNdeX (LInX): A new indexing procedure for process and product design and decision-making. *Journal of Cleaner Production, 12*, 59–76.

Knight, P., & Jenkins, J. O. (2009). Adopting and applying eco-design techniques: A practitioners perspective. *Journal of Cleaner Production, 17*, 549–558.

Ko, Y.-T. (2013). Optimizing product architecture for complex design. *Concurrent Engineering, 21*, 87–102.

Lee, J. J., O'Callaghan, P., & Allen, D. (1995). Critical review of life cycle analysis and assessment techniques and their application to commercial activities. *Resources, Conservation and Recycling, 13*, 37–56.

Lin, C., Madu, C. N., Kuei, C.-h., Tsai, H.-L., & Wang, K.-N. (2015). Developing an assessment framework for managing sustainability programs: A analytic network process approach. *Expert Systems with Applications, 42*, 2488–2501.

Liu, H.-C., Wu, J., & Li, P. (2013). Assessment of health-care waste disposal methods using a VIKOR-based fuzzy multi-criteria decision making method. *Waste Management, 33*, 2744–2751.

Liu, L. (2009). Sustainability: Living within one's own ecological means. *Sustainability, 1*, 1412–1430.

Mardani, A., Jusoh, A., & Zavadskas, E. K. (2015). Fuzzy multiple criteria decision– making techniques and applications – Two decades review from 1994 to 2014. *Expert Systems with Applications, 42*, 4126–4148.

Mascle, C., Baptiste, P., Sainte-Beuve, D., Camelot, A., 2015. Process for advanced management and technologies of aircraft EOL. *Procedia CIRP*, *26*, 299-304.

Matthews, W. A., Wood, S., & Connor, B. (2007). Sustainability and greenhouse gases: What are the issues for New Zealand? *Environmental Modelling & Software*, 22, 288–296.

Mayyas, A. T., Qattawi, A., Mayyas, A. R., & Omar, M. (2013). Quantifiable measures of sustainability: A case study of materials selection for eco-lightweight auto– bodies. *Journal of Cleaner Production, 40,* 177–189.

Mendoza, G. A., & Prabhu, R. (2004). Fuzzy methods for assessing criteria and indicators of sustainable forest management. *Ecological Indicators, 3*, 227–236.

Meyer, D., & Upadhyayula, V. K. (2014). The use of life cycle tools to support decision making for sustainable nanotechnologies. *Clean Technologies and Environmental Policy, 16*, 757–772.

Min, C.-O., Lee, D.-W., Cho, K.-R., Jo, S.-J., Yang, J.-S., & Lee, W.-B. (2011). Control of approach and landing phase for reentry vehicle using fuzzy logic. *Aerospace Science and Technology, 15*, 269–282.

Pearce, D. W. (1988). Optional prices for sustainable development. In D. Collard, D. W. Pearce, & D. Ulph (Eds.), *Economics, growth and sustainable environment*. London: MacMillan Press.

Phillis, Y. A., & Andriantiatsaholiniaina, L. A. (2001). Sustainability: An ill-defined concept and its assessment using fuzzy logic. *Ecological Economics, 37,* 435– 456.

Rabbani, A., Zamani, M., Yazdani-Chamzini, A., & Zavadskas, E. K. (2014). Proposing a new integrated model based on sustainability balanced scorecard (SBSC) and MCDM approaches by using linguistic variables for the performance evaluation of oil producing companies. *Expert Systems with Applications, 41*, 7316– 7327.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., & et al. (2004). Life cycle assessment. Part 1. Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30, 701–720.

Roca, L. C., & Searcy, C. (2012). An analysis of indicators disclosed in corporate sustainability reports. *Journal of Cleaner Production, 20*, 103–118.

Rostamzadeh, R., Govindan, K., Esmaeili, A., & Sabaghi, M. (2015). Application of fuzzy VIKOR for evaluation of green supply chain management practices. *Ecological Indicators, 49*, 188–203.

Rostamzadeh, R., & Sofian, S. (2011). Prioritizing effective 7Ms to improve production systems performance using fuzzy AHP and fuzzy TOPSIS (case study). *Expert Systems with Applications, 38*, 5166–5177.

Sabaghi, M., Cai, Y., Mascle, C., & Baptiste, P. (2015). Sustainability assessment of dismantling strategies for end-of-life aircraft recycling. *Resources, Conservation and Recycling, 102*, 163–169.

Sabaghi, M., Cai, Y., Mascle, C., & Baptiste, P. (2016a). Towards a sustainable disassembly/dismantling in aerospace industry. In *13th Global Conference on Sustainable Manufacturing (Procedia CIRP): 40* (pp. 156–161).

Sabaghi, M., Mascle, C., & Baptiste, P. (2016b). Evaluation of products at design phase for an efficient disassembly at end-of-life. *Journal of Cleaner Production, 116*, 177–186.

Santoyo-Castelazo, E., & Azapagic, A. (2014). Sustainability assessment of energy systems: Integrating environmental, economic and social aspects. *Journal of Cleaner Production, 80*, 119–138.

Schmidheiny, S. (1992). *Changing course: A global business perspective on development and the environment*. MIT Press.

Schmidt, W.-P., & Butt, F. (2006). Life cycle tools within Ford of Europe's Product Sustainability Index. Case study Ford S-MAX & Ford Galaxy. *The International Journal of Life Cycle Assessment, 11*, 315–322.

Shannon, C. E. (2001). A mathematical theory of communication. *SIGMOBILE Mobile Computing and Communications Review, 5*, 3–55.

Shiau, T.-A., & Liu, J.-S. (2013). Developing an indicator system for local governments to evaluate transport sustainability strategies. *Ecological Indicators, 34*, 361–371.

Strong, M., & Kirdar, U. (1992). Required global changes: Close linkages between environment and development. *Change: Threat or opportunity for human progress?* (pp. 11–24). New York: United Nations.

Tan, R. R., Aviso, K. B., Huelgas, A. P., & Promentilla, M. A. B. (2014). Fuzzy AHP approach to selection problems in process engineering involving quantitative and qualitative aspects. *Process Safety and Environmental Protection, 92*, 467–475.

Torra, V. (2010). Hesitant fuzzy sets. *International Journal of Intelligent Systems, 25*, 529–539.

Ungureanu, C., Das, S., & Jawahir, I. (2007). Development of a sustainability scoring method for manufactured automotive products: A case study of auto body panels. ASME 2007 international mechanical engineering congress and exposition. *American Society of Mechanical Engineers, 17*, 309–314.

Van Laarhoven, P. J. M., & Pedrycz, W. (1983). A fuzzy extension of Saaty's priority theory. *Fuzzy Sets and Systems*, *11*, 199–227.

Vargas Hernandez, N., Okudan Kremer, G., Schmidt, L. C., & Acosta Herrera, P. R. (2012). Development of an expert system to aid engineers in the selection of design for environment methods and tools. *Expert Systems with Applications, 39*, 9543–9553.

Vinodh, S., & Joy, D. (2012). Structural equation modeling of sustainable manufacturing practices. *Clean Technologies and Environmental Policy, 14,* 79–84.

Vinodh, S., & Rathod, G. (2010). Integration of ECQFD and LCA for sustainable product design. *Journal of Cleaner Production, 18,* 833–842.

Vollenbroek, F. A. (2002). Sustainable development and the challenge of innovation. *Journal of Cleaner Production, 10,* 215–223.

Wang, H., Bai, H., Liu, J., & Xu, H. (2012). Measurement indicators and an evaluation approach for assessing strategic environmental assessment effectiveness. *Ecological Indicators, 23*, 413–420.

WCED (1987). *Our common future*. London: Oxford University Press.

WorldBank (1992). *World development report: Development and the environment*. New York: Oxford University Press.

Yu, Q., Zhixian, H., & Zhiguo, Y. A. N. (2007). Integrated assessment of environmental and economic performance of chemical products using analytic hierarchy process approach. *Chinese Journal of Chemical Engineering, 15*, 81–87.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*, 338–353.

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning-I. *Information Sciences, 8*, 199–249.

Zhang, X., Lu, T., Shuaib, M., Rotella, G., Huang, A., Feng, S. C., Rouch, K., Dornfeld, D. A., Linke, B. S., et al. (2012). A metrics-based methodology for establishing product sustainability index (ProdSI) for manufactured products. *Leveraging technology for a sustainable world* (pp. 435–441). Berlin, Heidelberg: Springer.

Zimmermann, H. J. (1996). *Fuzzy set theory and its applications* (3rd ed.). Boston: Kluwer Academic Publishers.

CHAPTER 6 GENERAL DISCUSSION

Every year hundreds of aircrafts end up in landfills without an appropriate treatment. This thesis has been developed within the framework of the project “*CRIAQ ENV-412: Process for advanced management and technologies of aircraft end-of-life*”. It has been declared that, potentially, when an aircraft gets to end-of-life, around 15% of the weight can be reused (engines, auxiliary power units, avionic system, landing gear, etc.) and from the remaining, more than 70 to 75% potentially can be recycled. However, in real life, this proportion is far to be achieved in daily common aircraft end-of-life practices. An appropriate design for disassembly plays an important role to efficiently remove the essential parts without damage, and the use of innovative end-of-life strategies will help to achieve an appropriate recycling process. This dissertation was built up to ameliorate the existing managerial and technical methods by working on two important approaches that need to be considered toward a better aircraft recovery: “amelioration of aircraft design for end-of-life at the development phase”, and “improvement of end-of-life treatment methods”.

6.1 Amelioration of product design at the development phase

Disassembly appears as an inevitable activity for products not only at the end-of-life but also during the products life time and maintenance. In Chapter 3 was proposed a methodology that can be used to evaluate the components’ disassemblability at the design phase. The work developed in this chapter served as the subject of a manuscript that was accepted and published in “*Journal of Cleaner Production*”.

Disassembly-task is specifically defined as the act of separation. Separation is achieved when the mechanical connections such as fasteners, jo-bolts, rivets, i-locks, adhesive bonding, etc. for two components are clearly removed. Products are composed of different components assembled via different type of joints in an organized structure. Therefore, to disassemble a product, several disassembly-tasks might be required. These tasks would vary in terms of difficulty related to each one. The level of difficulty associated to a disassembly-task is referred as disassemblability. Different qualitative/quantitative parameters can influence the disassemblability of the components. These parameters may differ from one product to another. Based on the established parameters, a model can be developed to evaluate the disassemblability index for components in the product at the design phase.

After group meeting with the partners in the project CRIAQ-ENV412, a list of different disassemblability parameters was obtained. Having presented the problem and the importance to have a universal disassembly model, the group converged towards parameters with controllable characteristics at the design phase. Therefore, parameters such as: labor proficiency, workplace condition, material erosion, level of tools efficiency, rules, regulations, and standards, etc. were defined as uncontrollable factors and were not considered. Thus, based on the literature and taking the experience accumulated during the disassembly job, the selected parameters were summarized as: “Accessibility”, “Mating face”, “Tools required”, “Connection type”, and “Quantity and variety of connections”.

Considering the disassembly problem as a multi-criteria decision-making (MCDM) problem, a decision matrix can be constructed where the rows indicate the disassembly-tasks and the columns are the disassembly parameters. In our knowledge, no study has been reported with such a perspective into disassembly nor assembly problems. To solve this MCDM problem, TOPSIS was employed. Indeed, having TOPSIS employed we would be able to develop a ranking for disassembly-tasks in order to assign an index (disassemblability index) to every disassembly-task in the disassembly of the corresponding product. Therefore, a score between 0 and 1 will be generated for each disassembly-task.

Although the idea of having TOPSIS employed in disassembly problems is genuine, it might bring some limitations while solving the disassembly problems. In MCDM methods, the inputs of decision-matrix are required prior to solve the problem, and once an alternative is removed or added, the whole process for MCDM should be redone, which depending on the situation can be laborious and time-consuming (Sabaghi *et al.*, 2015). Particularly, in disassembly of an aircraft for which a huge amount of disassembly-tasks is required, the application of traditional TOPSIS is questionable. A minor change in the decision-matrix obliges the repetition of the process, which may not be easy to handle. Indeed, using TOPSIS, the disassemblability indices for the disassembly-tasks cannot be obtained independently (we need to have the decision-matrix of all the disassembly-tasks). This fact becomes an important issue especially in disassembly sequencing and product design. In complex products, components have relative positioning with each other.

For example removing one component may improve the “accessibility” and “mating face” for the next remaining components to be disassembled. As a result, using normal TOPSIS although it can provide good results, every time one component is removed the input parameters for all the remaining components should be revised in the decision-matrix. Consequently, count with a dynamic model is more preferred especially in the design phase where modifications and amendments are more common; to be able to evaluate the disassembly-tasks independently. For these reasons, we also proposed the hybrid DOE-TOPSIS model.

Design of experiment (DOE) is well known as an effective statistical method to design and analyze multi-variable processes. DOE helps to determine which subset of variables has the largest influence on the performance of a process. In our case, by applying DOE using analysis of variance (ANOVA), the effects of the parameters and their interactions on output from TOPSIS were analyzed. The sources of variation in this work come from the assessments collected from different decision-makers. Therefore, integrating DOE and TOPSIS leads to a regression model that allows a facilitated, dynamic, and independent disassembly-task evaluation process. First, the significant disassembly parameters and the interactions between them were pinned point. The results showed that among the analyzed disassembly parameters in the main structure of the aircraft, “*Accessibility*” and “*Quantity and variety of the connections*” are the most significant ones which can highly influence the disassembly-task. This result gives the idea to designers about the most important parameters they should respect during the design of the product. Then, a polynomial regression model was developed for estimating the disassemblability index. The results from ANOVA showed a 94.30% of reliability, and testified the adequacy of the model. The model was validated using 20 randomly generated inputs for the parameters, showing a very similar pattern to the one obtained from traditional TOPSIS. We used random inputs for the parameters, so we could eliminate the bias by giving all the alternatives an equal chance to be chosen.

The proposed model can be used by decision-makers, and designers for reengineering purposes. They can easily and practically evaluate the disassemblability indices among the different components/modules to improve the disassembly and in a broader scope recoverability of the future products at the end-of-life. Thinking about design for recycling using modularization, where disassemblability of the components plays an important role, having these results, allows designers to create modules that aggregate the most convenient components depending on the final destination of the module at the end-of-life. For example a module destined for recycling should be easy to disassemble as a whole piece; meanwhile the components inside can be difficult to disassemble but ideally composed of the same material. Hence, the team of experts involved in the design process must have a very detailed knowledge about the components' functions and implications on changing their material compositions in case of redesign. Aircrafts should be designed to be fail safe, but the widespread fatigue damage phenomenon has compromised this fail safety of the structure. To overcome this problem, the structure is designed in a way that is mainly composed of several aluminum components with different grades. These components are integrated in a very complex frame connected by many fasteners that, at the same time, are made of different metallic alloys. This alternate arrangement of different alloys and fasteners exist to ensure the integrity of the airframe from fatigue failure and crack spread, while providing a safe operating life. In the case of aircraft airframe recycling, applying modularization as an evolutionary redesign method with the goal to alleviate the cross contamination of different alloys may not be the most suitable technique. In a hypothetical case, applying modularization in order to keep the components with the similar alloy grade in the same module, still the existence of the fasteners (especially titanium rivets that are very hard to be removed) will greatly affect the quality of the aluminum retrieved from the recycling process. Perhaps, design for alloy recycling in the main structure requires a revolutionary redesign taking the benefits of new technologies such as additive manufacturing.

6.2 Improvement of end-of-life treatment methods

One of the major problems in recycling aircrafts is aluminum recycling. The homogeneity of recycled material in a recycling process is actively influenced by an appropriate disassembly/dismantling strategy. In recycling the carcass of the aircraft, it is suitable to separate and classify different aluminum grades into their main alloys family before sending them to recycling center. However, due to complexity in the aircraft structure, fully disassembly/dismantling or fully shredding the aircraft is not economically or environmentally viable, respectively. In the project CRIAQ ENV-412, eight different disassembly/dismantling strategies were implemented on a Bombardier Regional Jet aircraft. These strategies were defined as: "*A:* Systematic disassembly", *B:* "Shredding", "*C:* Smart shredding", "*D:* Gross cutting", "*E:*

Semi-gross cutting”, “*F:* Detail cutting”, “*G:* Smart disassembly”, and “*H:* Disassembly combined with cutting”. In Chapter 4 of this thesis, this eight strategies were described and evaluated in terms of 19 sustainability indicators. The proper selection of the indicators should be based on a deep understanding of the problem. Identification of the indicators was based on our observations and feedbacks from the experts. Due to inexactitude and fuzzy characteristics of the sustainability indicators, theory of fuzzy sets was used in the evaluation process. The results from this chapter were published in “*Resource, Conservation and recycling*” journal.

The sustainability analysis plotted in Figure 6-1 allows us to visualize the contribution levels of each strategy to environment, economic and social aspects. The 3-dimensional graph indicates environmental and economic contributions in axes *X* and *Y*, respectively. The social contribution is represented by the size of the bubbles and the score associated is shown in the center. From the graph, it can be seen that *Strategy A*, although it has the highest contribution to environment, the cost associated to implementation is very high; which compromises its economic contribution. Also low social score indicates the high level of safety risks by applying this strategy. In contrast, *Strategy B* while has good contribution scores in terms of social and economy, it appears to have a very low environment contribution. This is a drawback that might negatively influence for selecting this strategy for end-of-life treatment of the carcass. In the figure, four zones were established based only on the economic and environmental contributions. These divisions facilitate a better understanding of the graph. *Strategies A*, *G*, and *H* are located in Zone 3 (High environmental-Low economic). These strategies deal with disassembly-based tasks which results in better separation of the components. Thus, the amount of waste generation and homogeneity of retrieved material are lower and higher, respectively. On the other hand, cutting based strategies as *Strategy D*, *E*, and *F*, have a similar social and environmental performances. However, *Strategy D* (gross cutting) has better economic contribution. From this result, it can be generalized that cutting techniques have low environmental performance since during this procedure materials are cross contaminated which reduce the material homogeneity. At the same time the impact of these strategies on economic is not significant in compare with shredding techniques (*Strategies B* and *C*) in Zone 2 (Low environmental- High economic). No strategies were classified in Zone 4 (High environmental-High economic). With the aim to have strategies falling in Zone 4, more innovative technologies might be required.

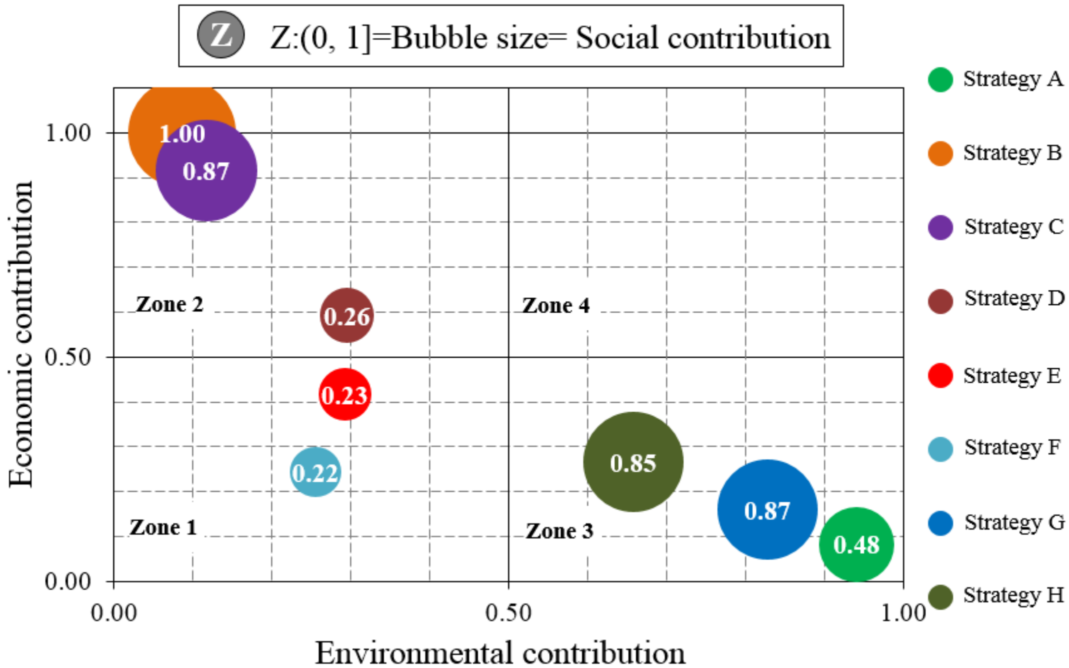


Figure 6-1 Contribution of strategies into sustainability elements; source: (Sabaghi *et al.*, 2016)

With the goal to have a robust understanding about the sustainability performance of each strategy, ten different risk scenarios were taken into account. The results showed that in environmental risky situations, "Systematic disassembly" and "Smart disassembly" are the alternatives of preference; while in economic and social risky scenarios, "Shredding" and "Smart shredding" are the ones desired, respectively (Figure 4-5). The outcome for this chapter can be used as a platform for managerial purposes in order to select the optimum strategy based on economic, social and environmental limitations that may exist in the project.

Finally, as a result of an internship at Bombardier Aerospace, it was raised the necessity of having a tool that allows assessing the sustainability of the products/processes. Thus, in Chapter 5 we developed a fuzzy-inference system to evaluate product/process sustainability (SAFT). The proposed method does not require generation of rules which simplifies the procedure and makes it more precise. The methodology SAFT was compared with fuzzy rule-base technique and pretty the same results were obtained. The work developed in this chapter served as the subject of an article that was accepted and published in "*Expert Systems with Applications*" journal.

Sustainability represents the simultaneously interaction of environment, economy, and social aspects. At the same time, each of these aspects involves several criteria. To better analyze a product in terms of sustainability, the problem might be broken down into elements and sub elements in a hierarchical format. The highest level in the hierarchy indicates the global sustainability assessment. The lowest level represents the influencing factors which refer to sub elements that affect sustainability of the product. The intermediate elements between highest and lowest levels correspond to guiding criteria. Guiding criteria reflect the successive categorization of environmental, economic, and social aspects. A list of guiding criteria and influencing factors were determined taking into account the state of art and the knowledge and experience of the expertise in design for environment department of Bombardier Aerospace. Unlike other studies, in SAFT methodology we consider the fact that different decision-makers or policy-makers in the company may have different ideas and belief about the relative importance of each element in the hierarchy on the overall sustainability of the product. This process of weight allocation is qualitative by nature because it is extracted from the opinions of the experts and consequently involves uncertain and fuzzy judgments. Therefore, Fuzzy AHP (FAHP) was used to assess the relative importance weights of the guiding criteria and influencing factors in the sustainability hierarchy.

Obviously, the weights obtained from one expert might be different from another. This is due to the fact that each of the experts has his own points of view and beliefs which we would like not to ignore. Therefore, there is a need to find a consensus among the different judgments. Using a simple average, although is simple and fast, it may not mirror the reality. Thus, it is wise to try a more precise technique to deal with this diversity of thoughts and with the aim to find an ideal solution. In SAFT methodology, Shannon's Entropy formula has been embedded with FAHP. Entropy is the measure of "disorder" in a set of collected data. The concept of entropy has a significant role in information theory, and sometimes is referred as measure of uncertainty. Thus, the integration of Shannon's Entropy formula with FAHP offers a more accurate weight allowance for guiding criteria and the influencing factors.

The sustainability of the product should be evaluated based on the influencing factors (lowest level in the hierarchy). Fuzzy techniques have been broadly used in different studies due to uncertainty and vagueness associated with these influencing factors. However, these studies are mostly based on fuzzy rules generation which is time consuming and also can lead to redundancy and inaccuracy. In contrast with fuzzy rule-base inference systems, SAFT methodology offers an easier and more practical platform to evaluate sustainability of products/processes since there is no need to generate rules. The effectiveness of the influencing factors are assessed individually through a fuzzy-inference technique. This also allows, the knowledge extraction from the experts is done individually which avoids one expert influences on the other's opinion. Thus, the final consensus is found via calculating the level of uncertainty among them.

CHAPTER 7 CONCLUSION

7.1 Conclusion and original contribution

It can be said that when a decommissioned aircraft gets to end-of-life, the first step is to remove the parts that can be further reused/remanufactured. This parts removal is highly influenced by an efficient disassembly job, since these parts should be kept intact for their rebirth. With a long perspective, this process can be facilitated back to the point of designing the aircraft. Thus, the main contributions of this part of the thesis are as follows:

- Based on the literature in our knowledge, there is a lack of a dynamic model that allows designers to assess the relationships among the components/modules in terms of disassembly at the development phase. In this thesis, based on the experience accumulated during the Bombardier Regional Jet airframe disassembly, we developed for first time a methodology where disassembly was considered as a decision-making problem that allows designers to evaluate the disassemblability of the components at the design phase.

- In our methodology, TOPSIS was employed which is a genuine approach *per se*. Afterwards, we introduced a hybrid DOE-TOPSIS method to develop a regression model which unlike traditional TOPSIS allows to obtain the disassemblability indices independently.

- The results showed that among the analyzed disassembly parameters in the main structure of the aircraft, “Accessibility” and “Quantity and variety of the connections” are the most significant ones which can highly influence the disassembly-task. This result gives the idea to designers about the most important parameters they should respect during the design of the product.

- The application of the model can help not only to improve the disassembly of the essential parts at the end-of-life but also for maintenance during the life time.

After parts removal, the remaining carcass prior to recycling should go under a series of disassembly/dismantling activities. One of the major problems in recycling aircrafts is aluminum recycling. Shredding has been extensively used as a pre-recycling method that allows transforming huge components of the aircraft into smaller and more practical dimensions. Fully shredding an aircraft as a whole piece, results in a mixture of different aluminum alloys with different grades and leads to a very low alloy homogeneity. Therefore, it is preferable to disassemble/dismantle the components with different grades of aluminum alloys into their main alloy families prior to shredding. The contributions of this work to address this problem are summarized as follows:

- Unlike previous works, this research proposed and described for the first time eight practical strategies mainly focused on categorization and sorting of alloys into their family series before sending to recycling centers.

- From an aircraft dismantler/recycler’s perspective, the selection of an appropriate disassembly/dismantling strategy in terms of sustainability might be required toward a green product/process. This gap has been fulfilled in this work by fuzzy evaluation of these strategies using 19 environmental, social, and economic indicators organized in a hierarchical structure.

- The strategies were evaluated and compared according to their sustainability performance under different risk scenarios. The risk scenarios provide a better understanding of the strategies to the project managers depending on the dismantler/recycler goal and the aircraft part of interest. For example if the part of the aircraft to be treated contains high proportion of hazardous materials, environmental-social friendly strategies are more desired. Similarly, appropriate strategies with less cost should be considered if the company faces economical limitations.

- Finally, a fuzzy-inference technique based on triangular fuzzy sets was developed to assess sustainability of products/processes. The proposed methodology was compared with fuzzy rule-base technique and pretty similar results were obtained. The SAFT methodology is more practical and easier since it is independent of having fuzzy rules. Generating rules in fuzzy rule-base can leads to redundancy and inaccuracy.

7.2 Limitations and scope of future works

As for most research works, there are always some prospects of improvements or further implementations. The following points can be suggested as future works of this research:

- Only five parameters were considered in the disassembly model based on our concern in current disassembly techniques in the main structure. Disassembly parameters might vary for different parts of the aircraft and the goal of the design team (maintenance or end-of-life). Identifying the right parameters in a tight contact with the design team, could translate better the reality and positively influence the reliability of the disassembly model. In addition, since disassembly is not the only concern for the design team, it would be attractive to consider other aspects of the product life-cycle into the model.

- To overcome the uncertainty and fuzziness potentially derived from MCDM problems, application of fuzzy MCDM methods such as fuzzy-TOPSIS can be useful to perform a more accurate disassembly evaluation.

- The proposed model could be employed in “design for modularity” for components clustering in order to define modules with high disassemblability while preserving the functionality and suitable sustainability. Again, this should be done in tight collaboration with an aircraft design team to make sure that decisions taken in design for disassembly does not compromise the other features and requirements of this complex product such as safety.

- In terms of disassembly/dismantling strategies, it would be great to implement the strategies presented on a new case study to extend, improve, and compare them with the theoretical evaluation that was presented in this work. The packages must be kept for recycling to have a better understanding on how different strategies can influence the recycling process.

- To scale up the mass treatment of end-of-life airplanes, keeping in mind the necessity of having the appropriate infrastructure to potentially employ robots and make the process more automated. Certainly, the cost-benefit and sustainability associated to such a system should be evaluated.

- The tool SAFT should be applied to different case studies to validate its strength and applicability. Additionally, more advanced programming languages can be used in order to broaden the application of the tool in more complex sustainability problems to make it user friendlier.

BIBLIOGRAPHY

AFRA. (2015). End-of-life aircraft value extraction: Dismantling & recycling. *Aircraft Commerce*. Retrieved from http://www.afraassociation.org/news_article2.cfm

AFRA. (2016). *Best management practice for management of used aircraft parts and assemblies and for recycling of aircraft materials*. Seattle, Washington: Aircraft Fleet Recycling Association.

Airbus, S. A. S. (2008a). *The A380: Recyclable by design*: Farnborough Airshow. Retrieved from http://videos.airbus.com/video/iLyROoafIluR.html

Airbus, S. A. S. (2008b). Process for advanced management of end-of-life of aircraft (PAMELA). Retrieved from http://www.pamelalife.com/english/results/PAMELALife-project_results-Nov08.pdf

Airbus, S. A. S. (2009). Tarmac Aerosave is operational. *News & Events*. Retrieved from http://www.airbus.com/newsevents/news-events-single/detail/tarmac-aerosave-is-operational

Asmatulu, E., Overcash, M., & Twomey, J. (2013). Recycling of aircraft: State of the art in 2011. *Journal of Industrial Engineering* 1-8. doi: http://dx.doi.org/10.1155/2013/960581

Asmatulu, E., Twomey, J., & Overcash, M. (2013). Evaluation of recycling efforts of aircraft companies in Wichita. *Resources, Conservation and Recycling, 80* 36-45. doi: http://dx.doi.org/10.1016/j.resconrec.2013.08.002

Bell, S., Davis, B., Javaid, A., & Essadiqi, E. (2003). *Final report on scrap management, sorting and classification of aluminum: Report No. 2003-22(CF)* Government of Canada: Natural Resources Canada.

Benhabib, B. (2003). Conceptual design. In *Manufacturing: Design, Production, Automation, and Integration*: CRC Press.

Blume, T., & Walther, M. (2013). The end-of-life vehicle ordinance in the German automotive industry – corporate sense making illustrated. *Journal of Cleaner Production, 56* 29-38. doi: http://dx.doi.org/10.1016/j.jclepro.2012.05.020

Boeing. (2013). *Current market outlook 2013-2032*. Seattle, Washington: Boeing Commercial Airplanes, Market Analysis.

Cacciottolo, M. (2011). How do you recycle a jumbo jet? Retrieved from http://news.bbc.co.uk/2/hi/uk_news/magazine/8542482.stm

Camarsa, G., Toland, J., Hudson, T., Jones, W., Eldridge, J., Thorpe, E., . . . Thévignot, C. (2013). Ensuring a soft landing for old aircraft. In H. Martin (Ed.) *LIFE creating green jobs and skills* (pp. 12-15). Luxembourg: European Union. doi: http://dx.doi.org/10.2779/33031.

Camelot, A., Baptiste, P., & Mascle, C. (2013, 28-30 Oct. 2013). *Decision support tool for the disassembly of reusable parts on an end-of-life aircraft.* Paper presented at Proceedings of 2013 International Conference on Industrial Engineering and Systems Management (IESM) (pp. 1-8).

Carberry, W. (2008). Airplane recycling efforts: Benefit Boeing operators. *Aero Magazine, 4,* 6-13. Retrieved from www.boeing.com/commercial/aeromagazine

CRIAQ-ENV412.). Process for advanced management and technologies of aircraft end-of-life, http://www.polymtl.ca/env412/index.php.

Das, S. K. (2006). Emerging trends in aluminum recycling: Reasons and responses. *Light Metals, 4* 911-916.

Das, S. K., Green, J. A. S., & Kaufman, J. G. (2008). *Application of the recycling indices to the indetification of recycle-friendly aluminum alloys*. http://www.phinix.net/services/Recycling/RecycleIndex.pdf.

Das, S. K., & Kaufman, J. G. (2007). Recycling aluminum aerospace alloys. *Light Metals, TMS* 1161-1165.

Das, S. K., Yedlarajiah, P., & Narendra, R. (2000). An approach for estimating the end-of-life product disassembly effort and cost. *International Journal of Production Research, 38*(3), 657-673.

Davis, J. R. (Ed.). (1999). *Corrosion of aluminum and aluminum alloys*. Materials Park, Ohio, USA: The Materials Information Society, ASM International.

Dayi, O., Afsharzadeh, A., & Mascle, C. (2016). A Lean based process planning for aircraft disassembly. *IFAC-PapersOnLine, 49*(2), 54-59. doi: http://dx.doi.org/10.1016/j.ifacol.2016.03.010

Del Brío, J. á., & Junquera, B. (2003). Influence of the perception of the external environmental pressures on obtaining the ISO 14001 standard in Spanish industrial companies. *International Journal of Production Research, 41*(2), 337-348. doi: http://dx.doi.org/10.1080/0020754021000024175

Deng, Q.-W., Yang, L.-P., & Wang, X.-W. (2009). *Process-based structuring knowledge in product development*. Paper presented at IEEE International Conference on Industrial Engineering and Engineering Management, Hong Kong.

Desai, A., & Mital, A. (2003). Evaluation of disassemblability to enable design for disassembly in mass production. *International Journal of Industrial Ergonomics, 32*(4), 265-281. doi: http://dx.doi.org/10.1016/S0169-8141(03)00067-2

Dubé, J.-P., & Bélanger-Gravel, J. (2011). *Développement sur le site de l'aéroport international de Montréal-Mirabel, d'un pôle industriel pour la gestion écologique des avions en fin de vie (rapport d'étape 1 de 2)*. Laval, Québec: JPD Conseil Inc.

Eckelman, M. J., Ciacci, L., Kavlak, G., Nuss, P., Reck, B. K., & Graedel, T. E. (2014). Life cycle carbon benefits of aerospace alloy recycling. *Journal of Cleaner Production, 80* 38-45. doi: http://dx.doi.org/10.1016/j.jclepro.2014.05.039

Eres, M. H., Bertoni, M., Kossmann, M., & Scanlan, J. (2014). Mapping customer needs to engineering characteristics: an aerospace perspective for conceptual design. *Journal of Engineering Design, 25*(1-3), 64-87. doi: 10.1080/09544828.2014.903387

Erixon, G. (1998). *Modular function deployment: A method for product modularisation.* (Doctoral thesis, KTH, Production Systems, Royal Institute of technology, Stockholm, Sweden). Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-2619

Feldhusen, J., Pollmanns, J., & Heller, J. E. (2011). End of life strategies in the aviation industry. In *Glocalized Solutions for Sustainability in Manufacturing* (pp. 459-464). Technische Universität Braunschweig, Braunschweig, Germany: Springer.

Feldmann, K., Trautner, S., & Meedt, O. (1999). Innovative disassembly strategies based on flexible partial destructive tools. *Annual Reviews in Control, 23* 159-164. doi: http://dx.doi.org/10.1016/S1367-5788(99)90079-2

Ferrão, P., & Amaral, J. (2006). Assessing the economics of auto recycling activities in relation to European Union Directive on end of life vehicles. *Technological Forecasting and Social Change, 73*(3), 277-289. doi: http://dx.doi.org/10.1016/j.techfore.2004.03.010

Gaustad, G., Olivetti, E., & Kirchain, R. (2012). Improving aluminum recycling: A survey of sorting and impurity removal technologies. *Resources, Conservation and Recycling, 58* 79-87. doi: http://dx.doi.org/10.1016/j.resconrec.2011.10.010

Gesing, A., & Harbeck, H. (2008, October 12-15th). *Particle sorting of light-metal alloys and expanded use of manufacturing scrap in automotive, marine, and aerospace markets.* Paper presented at Proceedings of REWAS 2008, Global Symposium on Recycling, Waste Treatment and Clean Technology, Cancun, Mexico.

Gesing, A., Stewart, C., Wolanski, R., Dalton, R., & Berry, L. (2013). Scrap preparation for aluminum alloy sorting. In *Recycling of metals and engineered materials* (pp. 1233-1249): John Wiley & Sons, Inc.

Ghadimi, P., & Heavey, C. (2014). Sustainable supplier selection in medical device industry: Toward sustainable manufacturing. *Procedia CIRP, 15* 165-170. doi: http://dx.doi.org/10.1016/j.procir.2014.06.096

Ghazilla, R. A. R., Taha, Z., Yusoff, S., Rashid, S. H. A., & Sakundarini, N. (2014). Development of decision support system for fastener selection in product recovery oriented design. *The International Journal of Advanced Manufacturing Technology, 70*(5), 1403-1413. doi: http://dx.doi.org/10.1007/s00170-013-5373-3

González-Benito, J., & González-Benito, Ó. (2006). The role of stakeholder pressure and managerial values in the implementation of environmental logistics practices. *International Journal of Production Research, 44*(7), 1353-1373. doi: http://dx.doi.org/10.1080/00207540500435199

Grimes, S., Donaldson, J., & Gomez, G. C. (2008). *Report on the environmental benefits of recycling*. Bureau of International Recycling (BIR), Imperial College London: Centre for Sustainable Production & Resource Efficiency (CSPRE).

Güngör, A. (2006). Evaluation of connection types in design for disassembly (DFD) using analytic network process. *Computers & Industrial Engineering, 50*(1–2), 35-54. doi: http://dx.doi.org/10.1016/j.cie.2005.12.002

Harbison, I. (2015). Scrapheap challenge. Retrieved from http://www.mromanagement.com/feature/aircraft-dismantling-spares?session_id=lrirk2icvei5u1nfe77se9sgo6

Harivardhini, S., & Chakrabarti, A. (2016). A new model for estimating End-of-Life disassembly effort during early stages of product design. *Clean Technologies and Environmental Policy* 1-14. doi: 10.1007/s10098-016-1142-y

Jahau Lewis, C., Yan, H.-S., & Shine, G.-Y. (1992). An expert system for machine screws selection in engineering design. *Expert Systems with Applications, 4*(1), 141-146. doi: http://dx.doi.org/10.1016/0957-4174(92)90048-W

Jeandin, T., & Mascle, C. (2016). *A new model to select fasteners in design for disassembly*. Paper presented at 13th Global Conference on Sustainable Manufacturing – Decoupling Growth from Resource Use. Retrieved from doi: http://dx.doi.org/10.1016/j.procir.2016.01.084

Kazmierczak, K., Mathiassen, S. E., Forsman, M., & Winkel, J. (2005). An integrated analysis of ergonomics and time consumption in Swedish 'craft-type' car disassembly. *Applied Ergonomics, 36*(3), 263-273. doi: http://dx.doi.org/10.1016/j.apergo.2005.01.010

Keivanpour, S., Ait-Kadi, D., & Mascle, C. (2013). Toward a strategic approach to end-of-life aircraft recycling projects a research agenda in transdisciplinary context. *Journal of Management and Sustainability, 3*(3), 76. doi: http://dx.doi.org/10.5539/jms.v3n3p76

Keivanpour, S., Kadi, D. A., & Mascle, C. (2015). End of life aircrafts recovery and green supply chain (a conceptual framework for addressing opportunities and challenges). *Management Research Review, 38*(10), 1098-1124. doi: http://dx.doi.org/10.1108/MRR-11-2014-0267

Kroll, E., & Hanft, T. A. (1998). Quantitative evaluation of product disassembly for recycling. *Research in Engineering Design, 10*(1), 1-14.

Latremouille-Viau, J., Baptiste, P., & Mascle, C. (2010). Airframe dismantling optimization for aerospace aluminum valorization. In S. Lee, R. Suárez & B.-W. Choi (Eds.), *Frontiers of Assembly and Manufacturing* (pp. 157-169): Springer Berlin Heidelberg.

Liu, S.-c., Shi, P.-j., Xu, B.-s., Xing, Z., & Xie, J.-j. (2005). Benefit analysis and contribution prediction of engine remanufacturing to cycle economy. *Journal of Central South University of Technology*, *12*(2), 25-29. doi: http://dx.doi.org/10.1007/s11771-005-0005-1

Mascle, C. (2013a). Design for rebirth (DFRb) and data structure. *International Journal of Production Economics, 142* 235-246. doi: http://dx.doi.org/10.1016/j.ijpe.2010.12.001

Mascle, C. (2013b). Product design for rebirth: Application to aircraft life cycle modeling. *Supply Chain Forum: An International Journal*, *14*(2), 70-83. doi: http://dx.doi.org/10.1080/16258312.2013.11517316

Mascle, C., Baptiste, P., Beuve, D. S., & Camelot, A. (2015). Process for advanced management and technologies of aircraft EOL. *Procedia CIRP*, *26*(0), 299-304. doi: http://dx.doi.org/10.1016/j.procir.2014.07.077

Mascle, C., & Zhao, H. P. (2008). Integrating environmental consciousness in product/process development based on life-cycle thinking. *International Journal of Production Economics, 112*(1), 5-17. doi: http://dx.doi.org/10.1016/j.ijpe.2006.08.016

Masui, K., Mizuhara, K., Ishii, K., & Rose, C. M. (1999, Feb 1st-3rd). *Development of products embedded disassembly process based on end-of-life strategies.* Paper presented at Proceedings of Environmentally Conscious Design and Inverse Manufacturing. First International Symposium On EcoDesign (pp. 570-575). doi: http://dx.doi.org/10.1109/ECODIM.1999.747676

Millet, D., Yvars, P.-A., & Tonnelier, P. (2012). A method for identifying the worst recycling case: Application on a range of vehicles in the automotive sector. *Resources, Conservation and Recycling, 68* 1-13. doi: http://dx.doi.org/10.1016/j.resconrec.2012.07.002

Monceaux, A., Kossmann, M., Wiseall, S., Bertoni, M., Isaksson, O., Eres, H., . . . Rianantsoa, N. (2014). Overview of value-driven design research: Methods, applications, and relevance for conceptual design. *Insight*, *17*(4), 37-39.

Perry, J. (2012). Sky-high potential for aircraft recycling. *Aircraft Maintenance magazine*, 2-5.

Remery, M., Mascle, C., & Agard, B. (2012). A new method for evaluating the best product end-of-life strategy during the early design phase. *Journal of Engineering design*, *23*(6), 419-441. doi: http://dx.doi.org/10.1080/09544828.2011.605061

Rose, C. M. (2001). *Design for environment: A method for formulating product end-of-life strategies.* (Department of Mechanical Engineering, Stanford University).

Rose, C. M., Ishii, K., & Stevels, A. (2002). Influencing design to improve product end-of-life stage. *Research in Engineering Design, 13*(2), 83-93. doi: http://dx.doi.org/10.1007/s001630100006

Rose, C. M., Stevels, A., & Ishii, K. (2000). A new approach to end-of-life design advisor (ELDA). *IEEE International Symposium on Electronics and the Environment* 99-104.

Sabaghi, M., Cai, Y., Mascle, C., & Baptiste, P. (2016). Toward a sustainable disassembly/dismantling in aerospace industry. *Procedia CIRP*, *40* 156-161. doi: http://dx.doi.org/10.1016/j.procir.2016.01.088

Sabaghi, M., Mascle, C., & Baptiste, P. (2015). Application of DOE-TOPSIS technique in decision-making problems. *IFAC-PapersOnline, 48*(3), 773-777. doi: http://dx.doi.org/10.1016/j.ifacol.2015.06.176

Schultz, P. B., & Wyss, R. K. (2000). Color sorting aluminum alloys for recycling-Part II. *Plating and Surface Finishing, 87*(6), 62-65.

Smith, V. M., & Keoleian, G. A. (2004). The value of remanufactured engines: Life-cycle environmental and economic perspectives. *Journal of Industrial Ecology*, *8*(1-2), 193-221. doi: http://dx.doi.org/10.1162/1088198041269463

Tarmac. (2016). Tarmac aircraft recycling. Retrieved from http://www.tarmacaerosave.aero/

Tasala Gradin, K., Luttropp, C., & Björklund, A. (2013). Investigating improved vehicle dismantling and fragmentation technology. *Journal of Cleaner Production*, *54* 23-29. doi: http://dx.doi.org/10.1016/j.jclepro.2013.05.023

Towle, I. (2007). *The aircraft at the end of life sector: A preliminary study*. University of Oxford.

Ulrich, K. T., & Pearson, S. A. (1993). *Does product design really determine 80% of manufacturing cost?* , (WP#3601-93). Massachusettes Institute of Technology, Cambridge.

Xing, K. (2003). *Development of an integrated framework for design recyclability (DFR).* (Advanced Manufacturing & Mechanical Engineering, University of South Australia).

Xing, K., Abhary, K., & Luong, L. (2003). IREDA: An integrated methodology for product recyclability and end-of-life design. *The Journal of Sustainable Product Design, 3*(3-4), 149-171.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*(3), 338-353. doi: http://dx.doi.org/10.1016/S0019-9958(65)90241-X

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning—I. *Information Sciences, 8*(3), 199-249. doi: http://dx.doi.org/10.1016/0020-0255(75)90036-5